THE ROLE OF FORESTRY IN FARMING SYSTEMS WITH PARTICULAR REFERENCE TO FOREST-GRAZING INTERACTIONS

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An analysis of global trends in the supply and demand for wood, crop and livestock products has shown that without close integration of their production there will be an increased disparity between supply and demand. Various estimates of production levels which will be necessary in the wood, crop and livestock sectors to meet increasing demand have failed to appreciate that any increase in production in one sector is dependent on developments in the other sectors; these developments are themselves often unlikely to happen because of the very developments occurring in the first.

An increase in the spatial and sequential integration of forestry, pasture and livestock husbandry has frequently been proposed to help improve sustainable production. From published information an analysis was made of the interactions of these components under varying conditions to try to identify the bio-physical situations in which integration is likely to be beneficial. The nature and magnitude of the interactions are highly variable and are specific in terms of diurnal and seasonal cycles, site, species, ecotypes and management regimes. However the interactions need to be understood before any observed responses can be explained. Consequently generalisations cannot be made about the conditions under which integrated systems result in improved overall production. Integrated systems which demonstrate increased or reduced production are described. Implications for interpreting research results are discussed since traditional research methodology of isolating parameters to test the response of organisms do not always take account of the influence on other parameters which may also have a bearing on the organisms' responses.

Semi-arid W Rajasthan (India) in 1971-72 is taken as a case study of the actual and potential role of agro-silvopastoralism, and in particular the role of fodder trees is evaluated, using data from over 110 technical publications. Inadequate experimental methods, interpretation and unrepresentative conditions of the research in relation to the actual situation in the farming systems has necessitated a number of assumptions to be made. These were derived from a critical evaluation of local research backed by information from elsewhere. Claims that the planting of fodder trees in rangeland will increase livestock productivity and economic development are disputed. Trends in livestock numbers and herd composition, land use patterns and status of vegetation suggest that the degradation of the natural resource base can partly be attributed to higher livestock numbers supported by fodder trees. The increased density of browsers on common rangelands (0.20 Adult Cattle Unit/ha) has resulted in a browsing demand during the monsoon estimated to be higher than the production. Hence fodder trees are unlikely to get established. Nevertheless, their growth has been encouraged on cropland where crop yields have apparently not been affected and measurable benefits can be seen. It is estimated that, in areas with 300-400 mm precipitation, fodder trees may produce 38 to 75% of the dry season forage from available croplands. A small-medium sized farm (c. 5 ha) may produce all the fuelwood needs (2.9 tonnes p.a.) of a household (6.3 people). Agro-silvopastoralism therefore appears primarily to benefit private land holders to the detriment of common land.

In other parts of the world, successful and sustainable silvo-pastoral systems have developed on private holdings or common rangelands with effective control over livestock densities and grazing. It appears unlikely that such systems could develop in areas where such conditions do not prevail.
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CHAPTER 1
INTRODUCTION

1.1. Objectives.
The aim of this study has been to develop an understanding of:

i) the interrelationships between forestry and farming, and in
   particular the livestock component of farming systems, in a number
   of different environmental situations;

ii) the benefits which may be obtained by appropriate
    integration;

iii) the technical and managerial factors which may promote the
    positive aspects of the interrelationships between forestry and
    livestock husbandry;

iv) the actual and potential role of integration between the two
    in promoting socio-economic development by referring in detail to
    Western Rajasthan (India) as a case study.

1.2. Definition of terms.
The terms Agriculture, Forestry and Socio-economic Development
themselves embrace wide concepts, and require further definition in
order to avoid ambiguity, and in order to set the boundaries of the
subject of this thesis.

1.2.1. Agriculture, forestry and farming systems.
Combe and Budowski (1978) and Stewart (1981) have suggested that
the available terminology of agriculture and forestry offers few
satisfactory definitions. The Shorter Oxford Dictionary (1964)
defines:

i) **Agriculture** as "the science and art of cultivating the soil; including the gathering in of crops and the rearing of livestock; farming (in the widest sense)";

ii) **Farming** as "the business of cultivating land, raising stock";

iii) **Arboriculture** as "the cultivation of trees and shrubs for use and ornament";

iv) **Forestry** as "the science and art of farming and cultivating forests, management of growing timber";

v) **Silviculture** as "the cultivation of woods or forests; the growing and tending of trees".

Ruthenberg (1980) defined a **farm** as a goal orientated system and an organized decision-making unit in which crop and livestock production is carried out with the purpose of satisfying the farmer's goals. Farms are systems (sets of related elements) because several activities are closely related to each other by the common use of the farm's labour, land and capital, by risk distribution and by the farmer's management capacity. The **farm unit** embraces all the resources which are under the management control of the farmer; there are however resources whose management is shared with others outside the farm unit (eg. communal grazing lands and water) and which are therefore not part of the farm unit as defined by Ruthenberg (1980); on these however the functioning of some of the farm unit's resources depends.

Combe and Budowski (1978) suggested that **agricultural production** in the broadest sense of the term, may imply the production of annual, semi-perennial or perennial plants for food or industrial raw
materials, or the production of animal products. However, referring to a number of examples in the literature, they suggested that the usually implied difference between silviculture and the tree production components falling within the field of agriculture depends on the product derived from the tree: silviculture implies the management of trees for wood (and resin) and refers to techniques of cultivation within the broader concept of tree resource management ie. forestry; however the cultivation of perennial tree crops for fruit (often referred to as arboriculture) forms part of agricultural production. Definitions have changed over time and can vary between countries. It varies between countries as to whether trees cultivated for leaves, oils or gums come under forestry or under agriculture.

It is apparent that there is no general concensus as to a clear delineation between agriculture and forestry and indeed such a delineation is unlikely to be perceived in most societies whose livelihood depends directly on a range of annual and perennial plant crops in close association with shrubs and trees, some of which may provide fuel, food and other useful products.

The factors which are likely to be taken into account by different people in their conceptual differentiation between forestry and agriculture include:

- ownership of the forest land and tree resource;
- intensity of management and/or cultivation of the tree resource;
- perceived functions of the tree resource: range of products and services.

For the purposes of this thesis, the following definitions are assumed: Forestry: all the protection and service functions as well as
the wood and fodder production of woody perennial plants managed to
different levels of intensity - and the techniques associated with the
achievement of the desired functions (referred to as silviculture).

**Farming systems:** classes of similarly structured farm units (as
defined above) which can be expected to produce similar products.

Included within the farming systems are the range of resources which
are outside the management control of farm units but on which the unit
relies significantly for its functioning (eg. common grazing land).

The forestry elements referred to in this thesis may therefore
either form part of the single farm unit, or be an outside resource
component with significant actual or potential impact on the management
unit.

**1.2.2. Socio-economic development.**

Westoby (1978) suggested that a nation can be said to be
developing socio-economically if:

i) its capacity to produce goods and services is expanding;

ii) those goods and services correspond to the real needs of its
    people;

iii) the expanded output of goods and services is so distributed
    that the most urgent of those needs are satisfied first and in an
    equitable manner.

While Westoby lists the needs in order of priority as food,
clothing and shelter, elementary health and education, (fuel could
presumably be included with food and shelter), Fontaine (1978)
suggested that they should refer to the needs identified by the
individual himself.
These definitions should, however, be further qualified. While a nation may be developing socio-economically in absolute terms, it may not be in relative terms if the population growth rate is higher than the rate of development; since it is the needs of individual people which have to be satisfied, it is the development rate relative to the rate of population increase which is important. To the first element of Westoby's definition should be added the requirement that the expansion of the capacity for production must be sustainable; there is in many circumstances a trade off between capacity for sustainable production and an output which matches real needs in the short or even medium term. While he does mention the need for equity in relation to the distribution of the expanded outputs, there is also a requirement for equity in the capacity to produce goods. There are, of course, problems of compromise between an individual's (or nation's) perceived needs - which may be short term - and a whole system's long term needs.

1.3. Rationale of the topic under investigation.

Before starting to analyse the various ways in which forestry may interact with farming and particularly with its livestock production component, it is worth outlining the reasons why a closer integration of forestry development with agricultural development may become increasingly important in many environmental and socio-economic situations.

1.3.1. Population, supply and demand for food, livestock and forest products.

The future demand for agricultural and forestry products will
depend on several factors including:

i) human population growth rates;

ii) the rate of change in purchasing power amongst different income groups;

iii) the rate of change in the proportion of populations represented in different income groups;

iv) the extent to which there may be alternative or increased uses for agricultural and forestry products (e.g. fuel in the form of alcohol distilled from wood or agricultural crops);

v) the extent to which alternative products may replace the demand for certain agricultural and forestry products.

Further there are two types of demand: the effective demand - i.e. that which is actually satisfied, and the underlying demand - i.e. that which reflects a need which is not satisfied due to the scarcity of the product or to the relatively high prevailing prices. A brief look will be taken at the world demand and supply situation.

Wood supply and demand.

The Centre for Agricultural Strategy (from now on referred to as CAS) (1980), based on IBRD figures, assumed that the world human population will change as shown in Table 1. Because the increase in world wood supply is not keeping up with the increasing demand, the CAS (1980) suggested that by the year 2000 there is likely to be a annual deficit of about 8% (410 million m$^3$) of the total world wood demand at fixed prices and by the year 2025 a 32% annual deficit (2948 million m$^3$) at fixed prices. The pressure on prices is therefore likely to increase and by the year 2000 the prices for round wood are likely to rise, perhaps by 30% in real terms, and by the year 2025 they may be
expected to rise by between 100 and 150% in real terms. Assumptions were made concerning numerous factors to arrive at such predictions and although it is not possible to outline all of these, a few are worth mentioning. The projected level of deficit in supply assumed a doubling of yield from existing forests and the cessation of destruction of natural forest. However, it will require considerable improvements in the management of forests to achieve a doubling of yields. Furthermore the natural forest area is declining by up to 16 million ha per year, an area much greater than the area of new plantations being created annually. Part of this loss of forest area is caused by the demand for new agricultural land (see below).

The likely shortfall of wood supply over demand levels (as predicted by the CAS, 1980) was based in part on assumptions of increased demand caused by the projected increase in population and certain projected economic growth rates. The average rate of economic growth (measured by gross domestic product -GDP) was expected to differ according to country group, and ranged for the period 1976-2000 from 1.2% per capita per year for low income Africa to 5% for capital surplus oil exporters. However, the projected rate of economic growth relied essentially on projections from averages in gross domestic product growth which took place in the different country groups between 1960-1970 and 1970-1976.

In time these may well be shown to be overestimates because of the general downturn in the world economy since 1973; indeed, the latest World Bank (1983) figures showed that the rate of GDP growth has been steadily dropping from the 1960-1973 average to 1982 in most country groups (and has fallen even more on a per capita basis). Hence
Table 1. World population, by economic groups, in 1976 and forecasts to 2025 (millions) (from CAS, 1980 and derived from IBRD projections).

<table>
<thead>
<tr>
<th>Group</th>
<th>1976</th>
<th>2000</th>
<th>2025</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low income Africa</td>
<td>2.7% growth to 2000</td>
<td>166</td>
<td>314</td>
</tr>
<tr>
<td>Low income Asia</td>
<td>2.0% growth to 2000</td>
<td>1049</td>
<td>1680</td>
</tr>
<tr>
<td>etc.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low income</td>
<td>1215</td>
<td>1994</td>
<td>3089</td>
</tr>
<tr>
<td>Low CPE</td>
<td>866</td>
<td>1139</td>
<td>1724</td>
</tr>
<tr>
<td>Middle income</td>
<td>844</td>
<td>1481</td>
<td>2242</td>
</tr>
<tr>
<td>High CPE</td>
<td>342</td>
<td>416</td>
<td>480</td>
</tr>
<tr>
<td>Industrialised</td>
<td>735</td>
<td>860</td>
<td>993</td>
</tr>
<tr>
<td>CSOE</td>
<td>12</td>
<td>26</td>
<td>69</td>
</tr>
<tr>
<td>TOTAL</td>
<td>4014</td>
<td>5916</td>
<td>8597</td>
</tr>
</tbody>
</table>

Note for country group definitions see Appendix 1.

although it is possible that projections of the likely demand for total wood products may be too high, projections of likely fuelwood or charcoal demand are likely to be realistic as the demand for fuelwood is believed to be very inelastic, at least up to a certain value of the ratio price to income per head. Fuelwood and charcoal demand was established to have made up 52% of the total world roundwood demand in 1976 and is expected to make up to 46% of the projected demand for roundwood in the year 2000 (CAS 1980); this underlying demand is based on a constant consumption per head and the population projections. When the fuel demand cannot be satisfied by wood as is increasingly the
case in many developing countries, the burning of agricultural residues or dung is resorted to with severe consequences for agricultural production; changes in nutritional habits may take place through pressure to use less fuel with potentially detrimental consequences for health.

Food supply and demand.

The elaboration of projections for likely world food demand and supply is just as difficult as for wood products.

While total dietary energy supplies in developing market economies (see Appendix 1. for definition of term) as a group, approached nutritional requirements in 1977, there is little evidence of a reduction in the number of severely undernourished people, estimated at 420 million in developing market economies in 1974/1976 (FAO 1980). Available supplies in developing countries fluctuate from year to year, and the distribution of these supplies is highly uneven between regions and groups of people. The incidence of abnormal food shortages is said to be increasing fast. The increase in food production has failed to keep up with population growth in more than half the developing countries. These are often the poorest countries and those where food production is already deficient.

While FAO (1980) suggested that developing countries could double food production by the end of the century by increasing production by 4% per year during the 1980's, and 3.7% per year during the 1990's, this would require such increased efforts and investments on several fronts that long term prospects for food production are disturbing; several sources suggest that food supplies per capita will decline and be insufficient to meet the demands of increasing population (Barr
In looking at past trends in food production to help project possible food production levels into the future, it is important to differentiate between levels of production due to changes in land area under production and to changes in yields per unit area.

The absence of reliable data on overall cropland trends has handicapped efforts to assess the impact of mounting pressures on the world's croplands. Although of doubtful reliability (ODI 1984), data exist from 1950 onwards for lands on which cereals are grown; cereals occupy 70% of the world's cropland and are the dietary staple of most societies (Brown 1978).

Although the area under grain expanded from 601 million ha to 758 million ha from 1950 to 1980, the area per person dropped from 0.24 ha to 0.17 ha. Most of the increase in the cropped area came from land of increasingly marginal agricultural potential although irrigation has also brought some otherwise unproductive land under cultivation. Concurrently, large areas of prime agricultural cropland have been lost to non agricultural uses such as open cast mines, hydroelectric dams, transport systems and urbanization. UN demographers expect the world's urban population to increase by 1.35 billion from 1980 to 2000; Brown (1978, 1981) suggested that if this projected increase created a need of 0.04 ha per person (and he provides evidence to support this estimated need), there will be a loss of a further 22 million ha of the most fertile agricultural land to urban development alone by the year 2000 (assuming that 40% of the land encroachment will take place on cropland).

Although the world demand for cropland is greater than ever
before, the amount of cropland abandoned each year (on top of that lost to urban and other developments) may also be at record levels. The reasons, usually the product of economic pressures interacting with ecological forces, include desertification, severe erosion, water logging, salinization of irrigated land, the diversion of irrigation water to non farm use and the lowering of underground water tables through excessive usage.

The UN (1977) has suggested that out of about 4000 million ha of arid and semi-arid lands 170 million ha are rainfed cropland, 250 million ha are irrigated cropland and the rest includes barren and grazing land; of the irrigated cropland about 25 million ha are subject to waterlogging, and 20 million ha subject to salinization with a reduction in productivity of about 20% for each. The UN in 1977 reported that one fifth of the world's cropland was degrading at a rate which was intolerable in the long run (Brown 1978).

The loss of natural fertility of the soil and the loss of soil through erosion (by wind or water) is not necessarily reflected in reductions in crop yields as the addition of fertilizers can compensate for such losses, at least in the short term. In the United States alone, the world's leading food producer and exporter, a US Department of Agriculture soil conservation survey in 1975 indicated that if inherent soil productivity is to be sustained, soil loss through wind and water erosion would have to be reduced by half, from the present 3 billion tons per year to 1.5 billion tons per year (Brown 1978).
World cereal yields increased from 1.04 tonnes per ha in 1950 to 1.62 tonnes in 1970, a 2.2% increase per year. From 1970 to 1980, however, yields increased by only 1.5% per year (Brown 1981). This slow-down is due to a combination of factors including the addition of marginal land to the world's cropland base, the loss of fertile land to urban and engineering developments, higher energy prices, a reduction in fallow in the dry land grain growing regions, a shortening of the fallow cycles in areas of shifting cultivation and the cumulative loss of top soil and fertility in major food producing regions.

There are a number of records indicating that grain yields are actually dropping in specific countries and situations (eg. Cross 1984, for Niger); a combination of the reasons mentioned above may contribute to such reductions, however the role of institutional factors can also be important (eg. effectiveness of administration, government policy). Nevertheless in some farming systems, and generally in countries such as Nepal, where the main objective of agricultural production is for home food consumption, there is increasing evidence that yields of many crops including maize have been declining over the last decade. The reasons for the decline in such cases can fairly certainly be attributed to an overall degradation of the natural resource base (eg. Bajracharya 1983, FAO 1983a, for Nepal).

Variability in world grain production appears to be increasing: production did not decline in any year between 1950 and 1970, but declined three times between 1970 and 1980 (Barr 1981). While unfavourable weather patterns have been partly responsible, it is the increasing susceptibility of crops to unfavourable weather patterns which is often more important: acreage adjustments have returned idled
land to production and added marginal areas where crops are more susceptive to disease and weather variability; new crops (e.g. maize replacing millet or sorghum) or crop varieties are often more susceptive to poor growing conditions (e.g. weather, reduced inputs due to their increased costs, infrequent supply etc.) (ODI 1984).

The possibilities of raising yields in the technologically more advanced countries are decreasing as the gaps between yields on farms and on experimental stations are narrowing fast; the backlog of agricultural technology waiting to be applied in the agriculturally advanced countries appears to be dwindling (Jensen 1978).

Brown (1981) relying on data from a US Department of Agriculture model of the world food economy, projected that by the year 2000 an increase of 10% in cereal cropland area will result in a drop of area per person from 0.17 ha in 1980 to 0.13 ha, i.e. nearly half the cereal crop area per person of 1950. For the food supply to double as suggested by FAO, the increase in yields per ha from now to the year 2000 would need to be greater than those achieved from 1950 to 1975 - a very unlikely development. The discrepancy in food availability per person is also likely to increase between developed and developing countries and between areas of fertile soils and marginal lands within developing countries. Population growth rates are higher in developing countries and the better land may be used by wealthier sectors of society while poorer sectors of society with higher population growth rates are pushed increasingly either onto marginal lands, or out of agriculture altogether. Increased pressure on marginal lands to provide food for a growing population is likely to lead to an increase in soil deterioration in cropping areas.
Livestock production supply and demand.

The problems faced in trying to predict supply and demand apply even more in the livestock sector for a number of reasons. The demand for various livestock products and functions varies widely in different parts of the world, according to tradition; the consumption of their food products, although beneficial, is not necessarily crucial to human nutritional requirements.

In developed market economies, there have been difficulties in adjusting production and processing capacities to stagnating or shrinking domestic markets; combined with the present reliance of much of the livestock production sector on feed grains and other products of systems requiring considerable energy and capital inputs, this makes it impossible to realistically predict demand and supply. In the USA there have been suggestions that there might be a decline in grain fed livestock in the future if the world grain prices rise; this would result in reduced production (Pimentel et al. 1980).

In developing countries, livestock perform a number of essential functions in farming systems apart from direct food production (Bernsten et al. 1983, Robinson 1983 see Annex 1; Roth et al. 1978). Animal food products have a high income elasticity of demand (Bernsten et al. 1983), and in the past two decades the growth in their consumption has exceeded that of their production resulting in production generally lagging behind demand (FAO 1983b).

Considerable increases in poultry and egg production have occurred in most developing countries, following modes of production similar to those of developed regions; to a lesser extent, improvements in production following similar patterns have occurred for pig meat and
milk production. Nevertheless analysts suggest that there will be considerable increases in demand in developing countries and particularly of beef and dairy products (FAO 1983b); a less optimistic scenario investigated to the year 2000 by FAO (1981) suggested an 80% increase in animal production (cattle, sheep and goats) with an increase in livestock numbers of 15%. Yet, with few exceptions, any increase in animal production over the last 50 years in developing countries has been due to livestock numbers and not to improved productivity (Mahadevan 1982).

The demand for the various livestock functions other than food (manure, power, social) must increase with human population growth. It is doubtful whether alternative technologies and modes of production can replace livestock in these roles to any significant extent. The non food values of livestock are frequently ignored when estimating the contribution of livestock to gross agricultural production. FAO (1983b) suggested that if the value of draught power and utilized manure (estimated on the basis of the values of mechanical power or chemical fertilizers which are replaced by livestock) are included, the total value of livestock production increases by almost one half in developing countries.

It can, however, be argued that the value of such products is in fact greater if one looks at the crop production foregone due either to manure utilization for other purposes or to the inability to utilize the full ploughing potential of livestock due to feed shortages resulting in weak stock. In some countries (eg. Pakistan, India), over 50% of the manure is used for fuel (Ward et al. 1980) the collection and sale of manure for fuel is a main source of income for a
considerable number of the rural landless. Further there is considerable evidence to show that the productivity of crops is highly sensitive to date of planting, particularly in parts of the developing world where rainfall is low. Levi et al. (1982) referred to a situation in Northern Nigeria where the groundnut yields were reduced by 10, 32 and 55% with planting dates 7, 14 and 21 days respectively after optimum planting date. In a semi-arid area of Kenya, Vonk (1984) found that during the long rains in one year, a delay in planting by one week resulted in missing 58% of the rainfall over the growing season. In many such marginal areas, the work performance of draught animals is poor at the crucial time of ploughing and planting due to the poor fodder resources which have prevailed during the dry season and this can often result in delayed planting (eg. Hoekstra, 1984 for Kenya). Efforts to use draught animals more extensively in West Africa have resulted in increases in labour productivity and significant yield increases over hand cultivation of 21% to 157% have been obtained for a number of grain and commodity crops (FAO 1983b).

No-tillage cropping systems may become more widespread in the future (Phillips et al. 1980) resulting in less reliance on livestock for ploughing in cropping systems; however, draught animal power is at present inadequate, the shortage being acute in some areas (eg. much of South East Asia) (Mahadevan 1982), and the demand for animal power is expected to increase by 0.8% per year in the future (Bernsten et al. 1983). FAO (1983b) has however calculated that to enable food production to increase in developing countries by 3.4% per annum until the year 2000, power input to agriculture would have to increase by 2.3% per year. If this involves a 15% increase in the number of
draught animals (see above), tractor numbers would have to increase by 400% unless the productivity of the existing draught animals also increases; since the required increase in tractor numbers seems out of the question in this time scale, an even higher number of draught animals would be required.

The contribution of livestock to the livelihood of people in the developing world is considerable. 12% of the world's population live in areas where food crops cannot easily be grown and where people depend entirely on the products obtained from ruminant livestock (Payne 1981). In mixed crop and animal farming systems livestock play an important role as food reserves and capital accumulation and in adding value to low value forage and family owned labour resources; livestock products are sold both to meet large cash expenses and to complement yearly income; their sale can often be the main source of income (well over 50%) (eg. Fonzen 1984, for Nepal). Small farmers sometimes earn more cash from this source than larger farmers within the same area and farming system (eg. Conlin et al. 1979, for Nepal), or derive more of their food from livestock than larger farmers (eg. Gautam 1983). Further, livestock can provide food products and income to the rural landless (Bernsten et al. 1983).

There is growing evidence, particularly from India, that where increased milk production on mixed crop and livestock farms has been associated with efficient marketing of the milk products, there has also been an increase in food grain production (Brumby 1981); a substantial part of the increased income, commonly 50%, even from sales of one or two litres a day, is spent on inputs for the cropping side of the farm enterprise.
The question arises as to how livestock production can be increased in developing economies given that increases to date have mainly been due to increases in numbers and not productivity. There are some large untapped areas of potential grazing lands. In Africa, vast areas of the subhumid and humid zone are however infested by tsetse fly and any hope of extending livestock production in these areas must rely on tsetse control, the adoption of trypanocidal drugs and the increased use of trypanotolerant breeds; the economic viability of such programmes depends considerably on increased meat prices to make the investment attractive (Mahadevan 1982). Large areas of South America are also suitable for pastoral activities; however in both Africa and South America, increases in grazing area would be largely at the expense of further loss of forest or tree cover (eg. Ormerod 1978, for Africa).

In most other parts of the developing world (including other parts of Africa), the problems facing attempts to improve productivity and production are mainly due to both a shortage of forage and grazing areas and to the predominantly low quality of that forage. There is considerable debate concerning trends in feed resources and concerning the causes of such trends. The UN in 1977 suggested that all 3600 million ha of rangelands in arid and semi-arid areas were deteriorating with a consequent increase in desertification in many areas; overgrazing by animals, due to dramatic increases in their numbers is stated as the cause for such deterioration. Sandford (1983), however, suggested that the situation is not so clear; referring to Africa, he suggested that the field data have revealed contradictory evidence concerning desertification although there are considerable problems in
defining the term. He also stated that the evidence has at times been altered to come in line with the expected conclusions concerning desertification; in the case of one country report to the 1977 UN Conference on Desertification, while the initial field data did not reveal much evidence of desertification, the draft report was amended subsequently at senior level to state that the evidence did reveal significant desertification.

Trends in livestock numbers in Africa are difficult to interpret since the large present numbers may be, at least partly, simply a rebound following the particularly low livestock levels of the late 19th century resulting from rinderpest epidemics (which often killed 80 to 90% of domestic livestock populations).

From Africa and elsewhere there is no disagreement, however, about the loss of grazing areas to cropping (FAO 1983; Fitzburgh et al. 1981, Mahadevan 1982, Ormerod 1978, Sandford 1983). This is particularly significant since these areas usually provide the best dry season grazing, a critical bottleneck to improved productivity (Robinson 1983, 1984, see Annexes I and II).

In Asia and the Far East, in the late 1970's the average area of permanent pasture per ruminant livestock unit was 0.12 ha. In India the average area devoted to forage crop production was 0.033 ha per animal (Mahadevan 1982); however the total area has not shown any significant change over the last 35 years (presumably due to the land shortage) hence the area per livestock unit which is devoted to the production of fodder is getting smaller each year. The average national shortfalls to livestock feed requirements reach 50% or more in some countries and crude protein levels of the feed are often below
ruminant maintenance requirements. The very high prices paid for dry season fodder in some parts of the world indicate both the value which livestock owners can place on their livestock, and the shortage of feed: Campbell (1980) reports market prices of 500 to 1500 Indian rupees per ton for fodder in western Madhya Pradesh (compared to 150 to 225 Indian rupees per ton for fuelwood).

Although considerable improvements in livestock productivity can theoretically be achieved on the present grazing resources given various inputs and changes in management and in attitudes, significant increase in effort on several fronts will have to be made if the trend towards higher livestock production is to change from being largely due to higher livestock numbers to include a component of higher productivity. Most increases in grazing land in developing countries will be at the expense of forest land while the expansion of cropland is often at the expense of the crucial dry or cold season grazing areas.

Conclusions

It seems clear from the preceding evidence, however incomplete and to some extent disputed, that both crop and animal food products and wood products are likely to be in short supply in the future, both on a regional and local basis. There are strong indications that a sectorial approach to likely supply and demand of natural resource products (from livestock, agricultural crops and forestry) fails to appreciate the interrelated nature of these resource production systems; in some cases assumptions regarding various production scenarios for the future for a particular commodity (livestock, crops, wood) fail to appreciate that the scenario is based on developments in
the other sectors which are unlikely to happen because of the very "improvements" in production of that first commodity. For instance, much of the addition to cropland is at the expense of the areas on which livestock rely for dry/cold season grazing and this erosion of the fodder base may make it impossible to sustain the very animals on which continued cropping depends (eg. Raintree 1983, for Kenya).

This is the context in which "agroforestry" has developed: the assertion that and the inquiry whether, the combination of farming and tree growing within single management units offers the possibility of avoiding the shortfall in production or the inconvenience of imbalance of production towards which "farming" and "forestry", pursued as separate systems, appear to be leading. Agroforestry has been defined as a "sustainable land management system which increases the yield of land, combines the production of crops and forest plants and/or animals simultaneously or sequentially on the same unit of land, and applies management practices that are compatible with the cultural practices of the local population" (King 1979). If forestry can be combined with farming in ways that enable a higher sustainable forestry and agricultural production than if their production and management were not integrated, the availability of agricultural and forest products could be increased. Within the broad concept of agroforestry systems, silvopastoral and agro-silvopastoral systems refer respectively to management systems in which some kind of forestry is integrated with livestock husbandry or with mixed agricultural systems which include a livestock and a crop production component.
1.3.2. Soil and Water Conservation

Trees can, when integrated in certain ways with agriculture, reduce the rate of soil degradation and even improve soil conditions by:

1) reducing erosion losses to either wind or water;
2) improving the nutrient status and water regimes in the soil horizons which are important to agricultural production.

1.3.3. Diversification of production.

Forestry can help increase the range of products which a farm unit may have at its disposal, either for direct use or sale.

1.3.4. Employment.

Most farming systems have at certain times of year lower labour demands for their agricultural enterprise. Certain forestry activities may coincide with such slack periods and therefore help utilize labour in a more productive way through the seasons. Conversely there may be conflict over labour at peak times.

1.3.5. Distance from areas of supply to areas of demand.

As transport costs associated with satisfying the farming system's demand for a particular forest product increase relative to total inputs costs and production returns, it may become increasingly advantageous to have a supply of the products closer to the farm and this may necessitate integration with the other production sectors of the farming system.
1.3.6. Conclusions.

There are a number of reasons for which it appears that a closer integration of forestry and farming may lead to sustainable benefits. To evaluate, for any situation, the optimum kind and extent of integration of forestry and farming, a wide range of factors have to be taken into account; such factors vary in their relative importance between different situations. They range from purely physical factors such as climate and soil fertility, to institutional factors such as land ownership, government policy, taxation and religious beliefs.
PART I

PHYSICAL FACTORS RELEVANT TO FORESTRY-GRAZING INTERACTIONS

A review of published literature on forestry-grazing interactions shows many authors consider that trees, either in intermittent strips or as scattered individuals can be beneficial to agricultural production. This can occur in a number of ways. Firstly, by improving the microclimate and the nutrient regime of associated pasture or crop plants or that of animals; secondly, soil erosion rates due to wind or rain can be reduced; thirdly, in the wet tropics and in some more arid areas, the role of tree fallow is seen as a means of improving the soil nutrient status which has been depleted by the combined effects of several years' crop production and soil exposure.

However other authors suggest that trees may have a deleterious effect on agricultural production. Firstly, there is conflicting evidence concerning the effect of trees on pastures; secondly, there are numerous accounts of the detrimental impact of ground or scrub vegetation on tree growth, and thirdly, conflicting reports concerning both the effect of different types of livestock on tree growth, and the effect of trees on livestock in terms of shade and shelter.

It is therefore worth reviewing in some detail the various mechanisms which are at play in tree - herbage and tree - animal interactions and this is done in Chapters 2 to 5 where a broad diversity of situations is described to show the range of interactions which can occur.
CHAPTER 2

CLIMATE AND PLANT PRODUCTION

At least in part it is the distribution in time and space of the principal climatological parameters such as light, temperature, humidity and wind which are responsible for the relative development of plants.

I shall look at each of these in turn even though there are usually interrelationships between these parameters in terms of their effects on a plant.

Concerning pasture plants, greater emphasis is placed on grasses and legumes since these two groups of plants have received most attention in research; they are usually thought of as the plants of most importance as animal fodder.

2.1. Light.

Changes in the duration, intensity and quality of light influence plant physiological and morphological processes in complex ways. Assuming other factors are not limiting, most tropical grass leaves (C4 plants) show an increasing rate of photosynthesis up to more than 60 klux of light intensity and therefore their leaves do not generally become light saturated in full sunlight (c. 60 klux) (Allen et al. 1976). Most temperate grasses and tropical legumes (C3 plants) show light saturation in individual leaves at 20 to 30 klux and therefore may become saturated at about one-third to one-half of full sunlight (Fig. 2.1) (Cooper et al. 1968, Humphreys 1981, Wong et al. 1980). However saturation for a plant or sward will be at higher light
Fig. 2.1. Response of net photosynthesis to light intensity in *Paspalum dilatatum* (tropical) and *Lolium multiflorum* and *L. perenne* (temperate) grasses. (From Cooper et al. 1968).

Footnote: a number of graphs, figures and tables in this thesis use different units for the same measures, but only where each illustrates a point independently without the need for intercomparison.
intensities as leaves in the lower part of the canopy receive less radiation (Fig. 2.2).

There is however considerable variation in the photosynthetic response to different light intensities between species, between genotypes of the same species from different locations and even between leaves in the same plant (Fig. 2.3) (Boardman 1977, Cooper et al. 1971), which may be separated by only very short distances - for instance Festuca rubra and Poa pratensis clones in the Cheviots with an altitudinal difference of 330 m (Grant 1968).

Some grass species are shade demanding; Wolters (1974) found in Central Louisiana that the grasses Uniola sessiliflora and U. laxa grown under full sunlight, 30%, 63% and 92% shade provided by woven cloth have an annual dry weight production of 193, 845, 1467 and 2045 kg/ha respectively (the treatments apparently influenced the plant microenvironment negligibly other than for light).

About half of the incident solar radiation falls within the 300 nm to 750 nm range and it is in this range that absorption takes place by the four principal plant photoreceptors (Fig. 2.4) (Smith 1981). The photosynthetically active radiation (PAR) occurs in the 400 to 700 nm wavebands while those responsible for stimulating the phytochrome pigment system are in the range c. 600 nm to c. 780 nm (red to far red usually referred to as: red = Pr or P660; far red = Pr or P730).

The effect of different patterns of varying light intensities and even qualities on the relative physiological development of plants are very complex.
Fig. 2.2. Relationship of crop growth rate (C) of Trifolium subterreneum and leaf-area index (LAI) at nine levels of illumination (in cal/cm²/day). (From Spedding 1971).

Fig. 2.3. Variation in photosynthetic rate between genotypes of perennial ryegrass (Lolium perenne), (from Cooper et al., 1971).
Fig. 2.4. Absorption spectra of the four principal plant photoreceptors. (From Smith 1981).
2.1.1. Light quantity.

Neutral shading (reduced natural light intensity with no change in spectral quality) affects different aspects of plant development in varying ways.

Under reduced light intensity, shade intolerant plants usually become etiolated and develop a high shoot to root ratio. Plants which are adapted or can adapt (including leaves in the lower canopy) to low light intensities often develop a steeper net photosynthesis response to low light intensities, and are therefore more productive at such intensities than sun-adapted plants or leaves (Boardman 1977, Fitter et al. 1981, Leverenz et al. 1979). For such plants or leaves, light saturation usually occurs at a lower light intensity than in sun-adapted vegetation. Shade plants usually exhibit low dark respiration rates and therefore low compensation points (level of light intensity where rate of CO$_2$ evolution = rate of CO$_2$ uptake).

The reasons for such different responses are varied and include: increases in specific leaf area (SLA) (leaf area to leaf weight), which in turn influences light interception and temperature regulation; increases in chlorophyll content per unit weight or volume of leaf; increases in the proportion of chlorophyll b relative to chlorophyll a and reductions in stomatal frequency and leaf conductance. Shade-adapted leaves or plants usually have a lower concentration of CO$_2$ fixing enzymes in their tissues (Boardman 1977).

The possibilities for anatomical adaptions are restricted in developed leaves, but adaptation through changes in the level of CO$_2$ fixing enzymes can take a matter of days (Boardman 1977).

In trees, the less light reaching the lower branches (the greater
the extent of canopy closure and canopy depth, the lower the rate of net photosynthesis. 

Baumgartner (1967) postulated that in the lower branches of a young Norway spruce forest near Munich, respiration exceeded photosynthesis resulting in a negative CO₂ assimilation rate. The suggestion did not consider the steeper response curve (and other adaptions) to low light intensities of shade compared to sun shoots (Leverenz et al. 1980). Nevertheless more complex and comprehensive models of photosynthesis in tree stands do suggest that in some species, when the canopy is closed, net photosynthesis may be negative in the lower levels of the canopy (Miranda 1981).

The differences between plants in response to shade influence the relative success of different species in pastures of mixed species. Ludlow et al. (1974) looked at the response of two tropical grasses, ruzi grass (Brachiaria ruziziensis cv. Kennedy) and green panic (Panicum maximum var. trichoglume cv. Petrie) and two tropical legumes, calopo (Callopoconium mucuniodes) and Siratro (Macroptilium purpureum cv. Siratro) grown in separate pots under different degrees of shading for 2 to 4 weeks. The relative growth rates of grasses were reduced by shading more than were those of legumes; this was due to a greater decrease in net assimilation, and also to the smaller compensatory increase in leaf area ratio (LAR) under shade in the grasses than in the legumes. The relative respiration rates of legumes were low at high illuminance compared to grasses but were little affected by shading, while that of grasses decreased sharply with decrease in illuminance.

The responses of decreased whole plant dry weight with increasing shade, decreased leaf area but increased LAR (leaves become larger but
thinner) and the proportion of leaf increasing at the expense of root development leading to a higher shoot to root ratio are typical of shade intolerant plants. These responses were found in the species tested except for green panic; although the latter showed the greatest reduction from 100% (369 cal. cm⁻² mean daily shortwave radiation) to 30% (133 cal. cm⁻² mean daily shortwave radiation) relative illuminance, both absolutely and relatively in plant dry weight with shading (a 7 fold reduction in dry weight), it showed a significant decrease in shoot to root ratio: from 8.24 at 100% illuminance to 5.13 at 30% and 3.53 at 10%. The much higher dry weight of green panic at 100% illuminance was reduced to approximately the same level as the other species at 30% relative illuminance. The net assimilation rate and relative growth rates of all 4 species were reasonably comparable at c. 30% relative illuminance. The number of ruzi grass tillers and calopo runners declined with reduced illuminance, their weight being unaffected, and the leaf area per tiller or runner increased with shading. However, in green panic the tiller number, tiller size and leaf area per tiller all declined with decreased illuminance.

The results suggest that shading reduced the competitive advantage (through greater relative growth rate) of grasses over legumes to a situation where both groups had similar growth characteristics. Shade may therefore be one way of helping to maintain a suitable grass-legume balance in tropical conditions - a balance which is difficult to establish (Ludlow et al. 1974, Mott et al. 1977, Whiteman 1980) but desirable since low nitrogen levels are a major limitation to productivity in most tropical areas (Breman et al. 1977, Felker 1979, Wong et al. 1980).
In contrast with the above result, Wong et al. (1980) found that green panic in mixture with siratro (both the same varieties as above) was at an increasing competitive advantage with decreasing levels of light intensity in subtropical S.E. Queensland, on a site with moderate nitrogen status. The advantage to green panic in that situation was due to several factors: its ability to increase nitrogen uptake by 34% and 52% under 60% and 40% sunlight respectively and to increase its leaf nitrogen levels. Photosynthesis rate in green panic leaves is directly related to leaf nitrogen in the range over which the levels were increased. The shaded swards were taller and the longer leaves (greater LAI) were distributed more evenly throughout the canopy. In siratro however, nodulation and $N_2$ fixation were reduced by shade, and the increased leaf area was not large enough to maintain the LAI. Furthermore siratro is known to lack the common shade adaptation which reduces dark respiration when light is decreased.

The results indicate that the general assumption that shade is beneficial in tropical pastures for the desirable balance of legume - grass species, cannot be applied to all situations and/or all mixtures of species. Siratro is not a shade - tolerant species and better adapted legumes would be required at lower illuminance levels. Further the latter result was the outcome of only 16 weeks experimentation and while the establishment year may be critical in determining the relative success of different species, it could be that as the soil nitrogen pool is depleted by green panic with time, the competitive advantage of green panic and siratro may be different subsequently.

Wong et al. (1980) referred to other situations where a positive response to shade has been found for some tropical grasses. $P. \text{ maximum}$
Fig. 2.5. Effect of nitrogen application on yield of tea at different light levels. (From Murray et al. 1966).
(guinea grass), *Brachiaria miliiformis* and *Digitaria decumbens* showed a substantial increase in total plant yield with shading down to 27% full sunlight when grown in pastures without nitrogen fertilizer. With addition of fertilizer, only *D. decumbens* showed an increase in yield at 70% and 45% daylight compared with full sun. A similar relationship in production response between different light intensities and nitrogen fertility has recently been shown for 5 out of 6 grass species tested in Hawaii (Eriksen et al. 1981) and has been known for other plants for a long time; Murray et al. (1966) showed how cocoa (*Theobroma cacao*) and tea (*Camellia sinensis*) had a greater yield with shade when nitrogen supply was poor; the leaves showed nitrogen deficiency. It is suggested that in a similar way to some shade demanding species, the chlorophyll of N-stressed plants is destroyed at high light intensities at a faster rate than it can be replenished (Eriksen et al. 1981, Newman 1983). The addition of fertilizer and full sunlight may enable the plant to outstrip the yield of plants grown in shade without fertilizer (Fig. 2.5).

Above ground dry matter biomass has been found to be higher with a certain degree of shading in some herbaceous legumes (eg. *Desmodium canum* (Gmel.) Schintz and Thellung "Kaimi clover" in Hawaii, Eriksen et al. 1982), in some shrubs (eg. *Cornus florida* and *Ilex vomitoria* in Texas, Blair 1982) and in some grasses even with high soil nitrogen levels (eg. *Panicum maximum* Jacq. in Hawaii, Eriksen et al. 1981, and under controlled illuminance with an ecotype from CIAT, Colombia, Navarro-Chavira et al. 1983). However in terms of sustained plant production useful to livestock, one should take into account shoot to root ratios which can determine resilience to grazing or to adverse
environmental conditions such as periods of water stress. Differential partitioning of biomass in the above ground parts may also be important if the proportions and the distribution of preferred plant parts are altered.

In their trials with six tropical grasses, Eriksen et al. (1981) found that for the minus N- treatments although the annual dry matter (DM) yield of shoots was higher with some shading, the sum of the annual yields of tops plus roots were similar for all light intensities. Regrowth after harvesting was slower in the shaded plots. Wong et al. (1980) found that for green panic, the increases in shoot to root ratio from full sunlight to 40% sunlight were 37% (from a ratio of 0.89) and 59% (from a ratio of 1.33) for a 4- and 8-weekly cut sward. Since there was a 30% increase in shoot yields in 8-weekly defoliated plants at 40% full sunlight, but a 14% decrease in yield in 4-weekly defoliated sward, it is likely that the influences of shade on shoot to root ratios are important for evaluations of likely sward response to grazing intensity. Further, where a number of species in a mixed sward respond differently in shoot to root ratios under different light intensities, one could expect shade and defoliation effects on the relative competitiveness of the various species.

Navarro-Chavira et al. (1983) found in guinea grass that the leaf to stem dry weight (DW) ratio declined as maturity progressed but remained consistently higher under the high irradiance regime. The DW ratio of leaf to stem declined from 13 at 15 days regrowth to 2.5 at 70 days, whereas the ratio for the low irradiance regime declined from 7.8 to 1.0. Although the total shoot DM yield was 40% higher under low irradiance after 70 days regrowth, the leaf DM accumulation was similar
under both irradiance regimes resulting in a lower increase in valuable fodder than would be expected from data referring to shoot yield only. On the other hand, Wilson et al. (1982) working on green panic found that the distribution of higher leaf bulk density towards the top of the canopy in the more mature grass swards under shaded conditions could assist preferential selection of the leaf portion.

The influence of shade on the rate of leaf senescence could also be important to secondary production. Wilson et al. (1982) found no difference between treatments in green panic and siratro while Navarro-Chavira et al. (1983) found that in guinea grass the onset of senescence in the first fully expanded leaf occurred at 28 days with low irradiance and was delayed until 36 days at high irradiance.

The extent to which shade has a variable effect on yield depending on the season is also of importance. Eriksen et al. (1982) found in 3 tropical legumes that there were significantly smaller reductions with shade in shoot yields during the cooler months, the period when pasture yields are lower in Hawaii and hence resulting perhaps in minor consequences for livestock. It could be however that in other situations a greater reduction may coincide with the time of year of greatest forage demand with more severe consequences.

In the case of annual pastures, and when it is desirable for plants to propagate by seed, the influence of shade on seed yields should be considered. Investigations by Eriksen et al. (1982) on 6 tropical legumes and by Collins et al. (1978) on two strains of subterranean clover in Western Australia have shown that decreasing levels of radiation have reduced flowering and seed yield.

Eriksen et al. (1982) investigated the rate of N₂ fixation in 6
tropical legumes under varying levels of shading from full solar radiation in Hawaii. With 30% reduction in light, the reductions in \( \text{N}_2 \) fixation levels closely followed the ranking for shade tolerance suggested for various species by Humphreys (1981): *Desmodium intortum* (Mill.) Urb. cv. Greenleaf and *Leucaena leucocephala* (Lam.) de Wit. cv. Hawaiian Giant (two relatively shade tolerant legumes) fixed 5% and 8% less \( \text{N}_2 \) respectively than in full sunlight; the two relatively shade intolerant *Macroptilium atropurpureum* (D.C.) Urb. cv. Siratro and *Stylosanthes guianensis* Schwartz cv. Schofield, fixed 36% and 44% less \( \text{N}_2 \) respectively. Humphreys' (1981) list includes some legumes which are rated as more shade tolerant than those investigated by Eriksen (1982). A sixth legume (*Desmodium canum* Gmel. Schintz and Tellung "Kaimi clover") showed a 9% increase in fixation at 30% reduced illumination and this may reflect the poor \( \text{N}_2 \) fixing potential of the plant (245 kg ha\(^{-1}\) at 100% illumination compared to 656 kg ha\(^{-1}\) for Hawaiian Giant); it was the only legume which also showed an increase in aerial DM yield at reduced illumination.

The effect of recurrent defoliation (every 8 weeks) on the shaded legumes over an 18 month period was also investigated. Defoliation resulted in the most severe decline in acetylene reduction activity in shade intolerant legumes; the results also indicated that the recovery of acetylene reduction took longer in legumes grown under shade than in full sunlight. This would have repercussions on the optimum grazing cycles and levels of grazing intensity for understorey grass/legume or legume pastures.

The response of plants to light intensity fluctuations of varying amplitude and frequency is far from clear. Yet it is often under such
conditions that plants grow when close to or under trees (see Chpt 4).

Ludlow et al. (1974) reported on a study with ruzi grass (Brachiaria ruziziensis cv. Kennedy) and calopo (Calopogonium mucunoides), in which in all cases it was the total amount of energy received which determined the overall growth of the plant, whether this energy was received for 10 days as 50% relative illuminance or 14 days as 33% illuminance. However such results are only likely to be achieved when both degrees of relative illuminance coincide with points on the linear part of the relationship between light intensity and net photosynthesis.

Clifford Evans (1966) mentioned that it was not, then, possible to demonstrate the importance of short periods of high light intensity (eg, sun flecks) interspersed in a long period of low light intensity diffuse radiation to the growth of plants on a forest floor.

Allen et al. (1976) referred to a few studies which had looked at the effect of light fluctuations on photosynthesis. Light periods of one or two seconds alternating with dark periods of one or two seconds increased the efficiency of PAR utilization by 20% to 100% compared to uninterrupted illumination. However it is not reasonable to apply these results to situations where plants are exposed to full light fluctuating with low light intensity periods. Further complications arise since, at least in some species (eg. Triticum aestivum L.), stomatal pores are able to integrate the effects of radiation alternating with darkness at cycles of 5 seconds thereby reducing transpiration and CO$_2$ uptake. The longer the cycles of fluctuation, the more the phytochrome system may be influenced, which may explain the report of a drop in the effectiveness of irradiance with
fluctuations of 10 to 100 seconds (the same plant which had shown a 100% increase in effectiveness with fluctuations of 1 second or more).

Huxley (1969) looked at the growth of cotton, mustard, radish, tobacco and tomato plants under strip shades at Makerere (Uganda). The plants had been grown under diffuse shade of c. 50% full daylight. They were then grown under strip shade (6 mm wide, orientated E-W) which transmitted overall 57% of full daylight, but which varied from full sunlight in unshaded strips to full shade. The shades were either fixed or moved laterally one strip width so as to subject any part of a leaf to alternate conditions of sunlight and shade for cycles of 86, 16 and 2.2 seconds. The differences between treatments (maximum c. 10%) were not significant (at 5% level) although in all experiments, DW increases were less in "slow moving than under fixed or rapid moving shades". It may however be that the leaves of the plants were operating within the light saturated range of their photosynthetic response curves. Different species may respond in different ways.

Sager et al. (1980) re-evaluated published data from a number of other investigations which had looked at the relative photosynthetic efficiency of intermittent and continuous light. Having reduced both light regimes to a common energy or photon flux density and comparing the photosynthetic rate between the different light modes, they concluded that the evidence from higher plants was not substantial enough to reach definitive conclusions.

It seems that the degree to which plants can be efficient at utilizing fluctuating high and low light intensities depends on several factors. All the physiological and morphological adaptions to shade which determine the range of the photosynthetic response curve
over which the light intensity fluctuates are important. The speed with which stomatal aperture is integrated with changing light intensity determines the extent to which CO$_2$ and water exchanges can take place over short periods of higher light intensity. Woods et al. (1971) looked at stomatal response to changing light in four tree species of known and varied shade tolerance. The illuminance required to open the stomata of most shade tolerant species was much lower than that for the shade intolerant species, and in all species the stomata opened faster than they closed in response to changes in illuminance (enabling a fast CO$_2$ uptake during short periods of higher light intensity). The shade adapted species was much quicker to reach new stomatal resistances. In terms of stomatal response, the following are therefore important: the rates of stomatal opening and closing; the magnitude of the change in resistance; the lag in response to a change in illumination.

Wong et al. (1980) found that the potential photosynthetic activity of shade adapted siratro leaves was much lower than that of leaves developed in full sunlight, but green panic responded the opposite way (Fig. 2.6). The latter has an unusual response which would be of great value to any plant in a shaded environment where intermittent high light intensities occur.

2.1.2 Light quality.

Fig. 2.4 shows that the spectral quality of radiation is important for different aspects of plant mechanisms. The role of the phytochrome pigment system is very important to various aspects of plant development and productivity. It is involved in the control or
Fig. 2.6. Light response curves of photosynthesis ($^{14}$CO$_2$ uptake) of a) green panic and b) siratro leaves developed under 100, 60 and 40% full sunlight in 8-weekly cut swards (data averaged for 2 regrowth cycles and expressed as a percentage of the maximum photosynthetic value for each species). (From Wong et al. 1980).
influence of flowering induction, vegetative growth (rate of leaf appearance, leaf length and width difference, internode elongation), tuber and bulb formation, tillering rate, shoot to root ratio, seed germination, leaf abscission and in some plants in the alternation between active and resting states (dormancy) (Cooper et al. 1968, Larcher 1975, Whiteman 1980). In legumes, nodulation is enhanced by red light and inhibited by infra red light (Ludlow 1978).

Phytochrome transformations are associated with photoperiod changes, and since many tropical pasture plants are able to measure diurnal time differences of 0.15 - 0.25 hours (Humphreys 1981), one could expect that small changes in light quality might influence the phytochrome pigment system enough to influence the development of certain understorey plants.

2.1.3 Light and fodder quality.

Differences in illuminance can have a significant effect on the quality of pasture in three major ways: the species composition can be altered; the rate of development of plants (such as postponing flower induction - as seen above) is changed; the chemical composition on the plants may be altered (independently of the changes due to the rate of development).

On various sites in the Grisons (Switzerland) the proportion of desirable pasture plants decreased with increasing shade from different forest tree species (Rieben 1957); a similar result occurred with pastures under orchards. In the South of the U.S. the two shade demanding grasses *Uniola sessiflora* and *U. laxa* are found primarily under tree canopies (Wolters 1973).
The chemical composition of pasture plants is influenced in complex ways by increasing shade. This effect varies in different species since their morphological responses to shade also vary. For instance a decreased root to shoot ratio may reduce the capacity of the plant to compete for soil moisture and nutrients. Nevertheless the moisture content of grasses often increases with shade. Tiedemann et al. (1971) in Arizona found that artificial shade increased the moisture content of some grasses; a perennial, plains bristlegrass \( \text{Setaria macrostachya} \) which is often found growing well under \( \text{Prosopis juliflora} \) increased its moisture content by more than 50% with 80% shade. A similar response was found with two grasses, crested wheatgrass \( \text{Agropyron desertorum} \) and basin wild rye \( \text{Elymus cinereus} \), in Idaho (Mayland et al. 1973) and in the tropical grasses investigated by Eriksen et al. (1981), Navarro-Chavira et al. (1983) and reported by Wilson (1982). However for the 6 tropical legumes investigated by Eriksen et al. (1982), reducing solar radiation had little influence on DM percentage. The effect on ruminants of a lower DM percentage is likely to vary between beneficial and detrimental depending on the relative importance of forage as a source of water and of reduced forage intake respectively; DM intake would be reduced since there is a maximum volume of fresh forage which can be consumed each day, unless an increased rate of passage and therefore digestibility also occurs.

Rieben (1957) reports that in the pastures under orchards, the P: Ca ratio was higher than desirable for animal health; the soluble carbohydrate levels were low such that high protein to carbohydrate resulted, leading to unfavourable digestion in ruminants.
Wolters (1973) found that protein concentration increased with shade in *Uniola sessiliflora* and *U. laxa* (see table 2.1) and referred to other evidence in the U.S. where shading increased protein, phosphorus, cellulose and lignin levels but reduced total available carbohydrates.

Table 2.1 Chemical analysis (%DM) of *Uniola sessiliflora* and *U. laxa* collected in September from different shading regimes (from Wolters 1974).

<table>
<thead>
<tr>
<th>Chemical Component</th>
<th>Percent shade</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.</td>
<td>30.</td>
</tr>
<tr>
<td>Protein</td>
<td>5.7</td>
</tr>
<tr>
<td>Fibre</td>
<td>33.0</td>
</tr>
<tr>
<td>Ash</td>
<td>9.9</td>
</tr>
<tr>
<td>Ca</td>
<td>.19</td>
</tr>
<tr>
<td>P</td>
<td>.03</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>49.0</td>
</tr>
</tbody>
</table>

In their investigations of tropical herbaceous legumes, Eriksen *et al.* (1982) and Wilson *et al.* (1982) found that the N concentration did not change significantly with varying radiation regimes, and the mineral concentrations either did not change or changed only slightly. In siratro total non-structural carbohydrates were found to be reduced by 2 percentage units from full sunlight to 40% sunlight, but the in vitro dry matter digestibility (DMD) was not altered (Wilson *et al.* 1982).

In the tropical grass species investigated to date, the
differences due to shade have been significant. Changes in DM
distribution in the above ground biomass, such as stem to leaf ratios,
clearly influence feed quality. These changes aside however, it has
generally been found that N concentration is increased with shading by
up to 60% with 30% shading from sunlight and 85% with 73% shading.
There is an interaction between soil fertility and shade and N levels.
The extent of the differences in N levels due to shade can also vary
according to season and the rate at which the N concentrations fall
during growth can also be affected by shade in a way which does not
seem to be directly related to different rates of maturation (Eriksen
levels are also generally found to be higher under shade. These
results led Eriksen et al. (1981) to conclude that since forage quality
and yield were improved under moderate shading, particularly at low
soil N levels, there is a possibility that animal nutrition could
benefit from pastures grown under moderate shading.

However in guinea grass and green panic, Navarro-Chavira et al.
(1983) and Wilson et al. (1982) respectively found that with increasing
shade, lignin levels were found to increase, and combined with other
chemical changes, this resulted in reduced in vitro DMD for comparable
plant parts (of up to 10-12 percentage units in the case of green
panic). Total non-structural carbohydrate concentrations also declined
with shade. A number of other investigations quoted by Wilson (1982)
on temperate and tropical grasses have generally shown decreases of
the order of 1-5 percentage units under a wide range of irradiances.
Similar changes due to shade have been found with 3 browse shrubs in
Texas by Blair et al. (1983).
The importance of the reduction in DMD to animal nutrition clearly depends on the actual levels of digestibility, since reductions in intake become more pronounced at lower digestibility levels.

While the percentage of lignin often accounts for the greatest proportion of the variance in in vitro DMD of tropical grasses, in some species and situations, eg. *Pennisetum purpureum* and *Panicum maximum* in Puerto Rico, in vitro DMD was found to be most strongly correlated with CP levels \( r = 0.93 \) and poorly correlated with lignin concentrations (Navarro-Chavira *et al.* 1983).

No investigations have looked at the CP digestibility (CPD) with shade; it could be influenced differently to DMD.

In New Zealand, Hight *et al.* (1968) investigated the possible role of reduced light intensity on the incidence of "ill thrift" in young sheep grazing autumn pastures dominated by grass. Plots of fast growing rye grass (*Lolium perenne* L) were artificially shaded in the autumn (22.4 ± 2.4% of light in unshaded areas at 1-2 pm) for 2-3 days prior to harvesting. Soluble carbohydrate levels were significantly \( p < 0.001 \) reduced by over 50% with shading while the proportions of cellulose and lignin were significantly \( p < 0.05 \) increased by over 10% (although cellulose and lignin contribute a much greater percentage DM than soluble carbohydrates). These changes led to a marked and rapid reduction in food intake and reduced liveweight gains by Border Leicester and Romney hoggets fed dried shaded pasture for 54 days. Towards the end of the trial, however, DM intake rose again, indicating that perhaps other environmental factors or a reduced plant growth rate, were starting to influence favourably the nutritive value of the shaded grass.

*Note: CP = Crude Protein*
The occurrence of grass tetany (magnesium deficiency in grazing ruminants) in Idaho, Nevada and Utah predominates during mid-spring on monocultured grasslands; it coincides with the rainy season when incident daily radiation is low. Mayland et al. (1973) looked at the effect of six weeks shading during growth on the chemical composition of established *Agropyron desertorum* (Fish.) Schult and *Elymus cinereus*. The increased concentrations of Mg and lower K/(Ca + Mg) values in shaded (25% of clear day radiation transmission) compared to unshaded plants could have reduced the incidence of tetany. However several other changes could have increased the likelihood of the incidence of tetany. The ratio of total forage nitrogen to total water soluble carbohydrate was on average 75% greater in both species when shaded. The total cations relative to total anions increased considerably (therefore so did ash alkalinity) in the shaded plants with a resulting increase in organic acids to maintain electrical neutrality. High concentrations of organic acids have been associated with reduced Mg availability to ruminants (due to chelation). The higher fatty acids concentrations also found with shading are capable of reducing the availability of Mg by forming water soluble soaps with it. As the forage tended to have lower DM contents, Mg intake could be reduced in two ways: i) a greater intake of feed is necessary to meet the DM and Mg requirements; ii) as the food is more "slushy", it is retained in the digestive system for shorter periods with a resulting reduced opportunity for Mg absorption. (Other environmental factors, such as improved moisture availability could be contributing factors to reduced Mg availability).

Toxin levels may be reduced by shading in some plants. Majak
(1977) reported reduced peak miserotoxin concentrations in Columbia milk-vetch *Astragalus miser var. serotinus* in *Pinus contorta* rangelands in British Columbia, with decreasing proportions of full sunlight from clear ground to less than 15% full sunlight regimes (although an interaction with temperature effects cannot be ruled out).

2.1.4. Conclusion.

Clearly variations in light regimes influence plants in complex ways and different species show a number of responses which can vary both qualitatively and quantitatively. The evidence concerning certain responses makes it possible to draw some conclusions with reasonable confidence.

Under conditions of nutrient stress, some degree of shading can result in higher yields than under full sunlight in plants which would, under higher soil fertility, respond by increased yield up to full sunlight intensity. However the fertility level at which this response occurs will vary according to the fertility requirements of a particular species. The question arises therefore as to whether higher yields could be achieved under full light intensity with species more tolerant of low fertility. No detailed, comparative work seems to have been done on this aspect. It would merit investigation.

A number of species respond to lower irradiance by developing high shoot to root ratios. Shading trials which only look at yield response in terms of aerial biomass, and then only over short periods of time and/or with only one harvest providing the data, may give unrealistic indications of how the species is likely to respond in real silvo-pastoral situations. The lower the root to shoot ratio, the greater
the reduction in competitive ability is likely to be in situations of moisture or nutrient stress; the susceptibility to grazing pressure may be greater. If there are any differences in the degree of the influence of shade according to season, the importance of the influence will depend on the seasonal variation in the value of a unit amount of pasture to the livestock enterprise.

The suggestion which has often been made that some degree of shading is likely to improve the competitive advantage of legumes in grass-legume mixtures in the tropics and sub-tropics, cannot be generally accepted. The relative success of the grass and legume components of the pasture mixes must vary with the particular species and ecotypes concerned and with their individual responses to shade in a number of characteristics under the specific environmental conditions of the site. It would seem important that more trials are carried out with species which are thought to be shade tolerant, rather than with species which may be successful under full sunlight in tropical pastures and are characteristically light demanding eg. siratro; this would be particularly important amongst the legumes.

The results also suggest that trials under field conditions which compare the effect of a growing tree canopy on pasture production with the pasture yields of a tree-less control are likely to underestimate the production levels which could be achieved in the understorey by more shade tolerant species. The converse situation is equally relevant: a trial comparing the productivity of a wooded site with one which has recently been cleared of trees, would not give a good indication of the potential of the cleared site until more light demanding and productive species make up the pasture.
Concerning the changes in pasture quality with shading, the situation is not always clear. CP levels are generally increased in grasses with increasing shade and since a shortage of protein is often the main limiting factor to livestock production in tropical and subtropical countries, it has been assumed that higher CP levels would be an advantage. The more recent investigations however indicate that changes take place in the concentrations of a whole range of other chemical constituents. An understanding of how the interactions between these constituents change qualitatively and quantitatively through altered relative concentrations (eg. lignin and CP), and what these changes mean in terms of ruminant nutrition, is required before predictions can be made as to the significance of these changes in terms of animal production.

These conclusions assume that other environmental factors are not altered with the addition or removal of shade; most of the trials quoted so far have included changes in the radiation regime of plants using artificial shade which altered other environmental factors only to a small extent. However, similarly to the effect of shade trees on coffee, cocoa and tea plants (Willey 1975), the influence of trees on pasture production and composition are mediated through changes not just in light intensity, but also in the temperature, moisture and wind regimes which are discussed in the next sections, and through changes in soil fertility.

Finally, pasture plants which are appropriate for tree-pasture mixes are those in which the rate of decline in sustainable yields of suitable quality is as low as possible under reduced light intensity; influences on vegetative and sexual reproductive capacity are therefore
also important. Where yields and quality can actually be improved, so much the better.

2.2. Temperature.

Plants are influenced in 4 ways by temperature: i) their physiological processes and ii) their morphological developments are directly affected; iii) the rate of mineral cycling and nitrogen fixation are in part affected by temperature, these in turn influencing plant growth; iv) with increasing temperature there is a higher evaporative demand which may reduce soil moisture to levels which become limiting to plant growth (this last point will be discussed in section 2.3).

Fig. 2.7 shows a generalized growth response curve for legumes and grasses to different constant temperatures. However there is still some debate over the relative growth responses of tropical legumes and tropical grasses at high temperature; Sweeney et al. (1975) proposed that there should be a strong shift to the left for the response curve of grasses and that some legumes respond better to higher temperatures (Fig. 2.8).

It would seem likely that different pasture species respond in different ways, both qualitatively and quantitatively to temperature extremes, temperature fluctuations and temperature – light, temperature – nutrient, and temperature – water interactions. Furthermore considerable differences occur in the response of clones within species: Grant (1968) found such differences in the Cheviots for Festuca rubra and Poa pratensis in the rate of leaf elongation and the rate of leaf tillering in all growing periods and in some growing
Fig. 2.7. Generalized representation of dry matter production responses of temperate and tropical pasture species to temperature. The growth index represents dry matter production relative to maximum dry matter production of tropical grasses at their optimum temperature. (From Whiteman 1980).
Fig. 2.8. Thermal response curves proposed by Sweeney et al. (1975) with the shift to the left of the grass response curve.
periods for the rate of leaf appearance.

The two important aspects of temperature are: i) seasonal changes — usually expressed as daily means; ii) diurnal variations; and how these interact with light and moisture regimes.

The lethal minimum temperature varies — for some tropical grassland species it occurs at $0^\circ C$ to $-2^\circ C$ while some temperate species can survive temperatures below $-20^\circ C$ (Whiteman 1980). At low temperatures, growth is slow due to the slower rates of the reactions involved with photosynthesis and due to stomatal closure. As the temperature rises, its influence on the net assimilation rate is determined by the balance between its effect on photosynthesis and on respiration rates. Photosynthesis is influenced by temperature only through the dark reactions where the rates of $CO_2$ fixation and reduction increase as the temperature rises. The $Q_{10}$ of respiration has an average of 2 but is slightly higher at lower temperature, and slightly lower at higher temperatures (Larcher 1975). As the temperature increases above that which is optimum for growth, photosynthesis becomes inhibited and photorespiration and dark respiration increase so that net photosynthesis approaches zero (Whiteman 1980). Further increases in temperature lead to the death of the plant.

Overheating is a problem in the sub-tropics and semi-arid regions where day air temperatures may be as high as $40^\circ C$ and the temperature of leaves directly exposed to the sun may be $20^\circ C$ higher (Ferwerda 1979).

In these areas low night temperature can also significantly reduce growth and survival. At a day temperature of $20^\circ C$, a reduction in $Q_{10}$ = effect of a $10^\circ C$ temperature rise on the rate of a chemical reaction.
night temperature to 8°C and to 4°C reduced the growth rate of buffel grass (Cenchrus ciliaris) by 60 and 90% respectively (Whiteman 1980).

In the tropics, high temperatures affect legumes more than grasses, and the growth of legumes with a few exceptions, is more sensitive to low night temperature than grasses; they are also more sensitive to frost (Whiteman 1980). In higher latitudes (and at high altitudes) low dry air temperatures and low soil temperatures significantly reduce the time over which pasture species may grow.

However the slopes of both the photosynthesis curve and the respiration curve in response to temperature vary between species and even between ecotypes (Fig. 2.9) (Alcock 1969). Hence mean temperature and temperature fluctuations will have different effects on the net assimilation rate of different species and ecotypes. For instance Mediterranean ecotypes of Lolium perenne and Dactylis glomerata possess a higher growth rate than northern ecotypes at low temperatures (5°C), and tend to become dormant at high temperatures (Cooper et al. 1968); however, between ecotypes, the different distribution in assimilates within the plant may also affect the "rate of growth": in Mediterranean ecotypes, the leaf expansion is active at 5°C leading to a higher leaf area ratio and few soluble carbohydrates, while northern forms have little leaf expansion at that temperature but accumulate soluble carbohydrates.

Diurnal fluctuations and their amplitude affect the growth of pasture species in different ways; it is enhanced in some species by cold nights and reduced in others (Cooper et al. 1968). The maximum
Fig. 2.9. Respiration rates of 2 *Lolium perenne* clones with increasing air temperature.

(From Alcock 1969).
dry weight (DW) accumulation by *Stylosanthes humilis* (a C3 grass) was found with a temperature regime of 33°C during the day and 25°C during the night, while a 33°C/18°C regime depressed the dry weight accumulation substantially (Sweeney et al. 1975).

The initiation of physiomorphological changes (seed germination, rate of tiller development, leaf appearance, leaf length and width increase) is also influenced by different temperature means and fluctuations, and varies in different species and ecotypes. The temperature regime required for a specific stimulus can be different from that required for optimum growth and may interact in some way with photoperiod responses. For instance the temperature influences the timing of flowering by either slowing or hastening the response to photoperiod. The optimum temperature for root growth is usually (at least in temperate grasslands) lower than that for shoot growth (Tainton et al. 1968). The rate of tillering in *Lolium perenne*, *Holcus lanatus*, *Dactylis glomerata* and *Agrostis tenuis* increases slightly with a day time temperature rise from 7°C to 15°C and increases markedly with a fall in night temperature from 7°C to 2°C (Alcock 1969).

The effects of temperature on the digestibility of grassland species are considerable. In a range of temperate grasses, a drop in digestibility (associated with a drop in percentage soluble carbohydrates) occurred with an increase in the day – night temperature from 21°C/13°C to 32°C/24°C when harvested at the same physiological age (2 days after the 5th leaf reached maximum length) (Whiteman 1980). In tropical grasses increases in temperature affect digestibility more indirectly, by hastening plant development. Table
Average change in DMD (% units) per °C increase in growth temperature.

<table>
<thead>
<tr>
<th></th>
<th>Tropical</th>
<th>Temperate</th>
<th>Tropical</th>
<th>Temperate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tops</td>
<td>-0.60</td>
<td>-0.56</td>
<td>-0.28</td>
<td>-0.21</td>
</tr>
<tr>
<td>Leaf</td>
<td>-0.57</td>
<td>-0.64</td>
<td>+0.19</td>
<td>-0.09</td>
</tr>
<tr>
<td>Stem</td>
<td>-0.86</td>
<td>-0.76</td>
<td>-0.27</td>
<td>-0.22</td>
</tr>
</tbody>
</table>

Table 2.2 Effect of temperature on herbage dry matter digestibility (DMD) (from Wilson 1982).
2.2 shows the effect of controlled temperature regimes on the DMD of various plant parts from a number of studies reviewed by Wilson (1982). Clearly, high temperature has a strong detrimental affect on the DMD of both temperate and tropical grasses, but a much smaller effect on legumes, although care should be taken not to generalize from the data on tropical legumes since these are the results of too few investigations. Nevertheless these results may explain why only small changes in DMD with temperature have often been noted in legumes. Although these changes due to temperature may partly be a result of faster maturation, Wilson (1982) also reports from a number of grasses where plant parts of comparable age and size were of higher digestibility when grown at lower temperatures. In most species lower night temperatures increase the digestibility of the leaf, the stem or both (Whiteman 1980).

The rate of nitrogen fixation by legumes is markedly influenced by temperature. For *Trifolium repens* the maximum rate of nitrogen fixation is reached where root temperature equals 20° to 23°C and is negligible at 5°; in tropical legumes, nodulation and nitrogen fixation seem to be optimal at c. 30°C though in some varieties they are stimulated by soil temperature of up to 34°C (Whiteman 1980).

The rates of water and nutrient uptake are also influenced by soil temperature.

The rates of organic matter decomposition and subsequent nutrient availability are significantly influenced by the temperature found in the soil (Heal 1979). The general effect of a rise in temperature from 5°C to 30°C is to increase the rate of organic matter decomposition. However the subsequent availability of minerals to
plants is determined by a complex range of factors including the rate of loss of nitrogen to the atmosphere and the degree of immobilization of nutrients in the microflora or on soil particles. At temperatures of about $30^\circ C$ nitrogen losses to the atmosphere in the form of gaseous ammonia ($NH_4^+ - N$) may be significant (Floate 1970, Wong et al. 1980). These losses decline with decreasing temperature.

In the Scottish uplands, evidence from experimentation with the pasture plants Agrostis tenuis, Festuca rubra, Nardus stricta, and with sheep faeces from ingestions of the same plants (Floate 1970) indicate that there are likely to be fluctuations over the year in net mineralization (mineralization minus immobilization) of N and P at constant temperature (Fig. 2.10). The amplitude of the fluctuations and their timing in relation to the start of decomposition vary for different grasses, between grasses and faeces, and between incubating temperatures. Generally N net mineralization rate increased for the first 3 weeks then dropped significantly and even became negative in some cases (rate of immobilization of N being greater than rate of mineralization). After 6 weeks the rate of net mineralization increased again. For P, at low temperature ($5^\circ C$ to $10^\circ C$) there was a flush of mineralization during the first 3 weeks, followed by significant immobilization, while mineralization increased relative to immobilization after about 6 weeks at $10^\circ C$ but not at $5^\circ C$. The length of time during which surface soil temperatures are above $10^\circ C$ is crucial to the relative availability of N and more particularly P as net mineralization may become positive again at some point after 12 weeks. Nevertheless Floate (1970) suggested that the rate of mineralization of N and P from faeces may be less adversely affected by
Fig. 2.10. The effect of temperature on the production of mineral P during incubation of a) Agrostis - Festuca (A), b) Nardus (A), c) Agrostis - Festuca (B) faeces, and d) Nardus (B) faeces. [(A = annually accumulated plant material; B = faeces fed on monthly-cut plant material).]

- incubated at 30°C
- incubated at 10°C
- incubated at 5°C (From Floate 1970)
low temperatures (10 °C or below) than the decomposition of plant materials which was best achieved at higher temperatures (30 °C).

The effect of trees on understorey plants, mediated through temperature influences and through other factors which are interrelated with temperature, depends on the qualitative and quantitative influences of the trees on the daily and annual temperature regime (see Chapt. 4), and on the degree to which individual plants respond to these changes.

In terms of temperature influences on plants mediated through soil nutrient cycling, the important point is whether the trees influence the temperature where the gradient on the temperature response curve of the process in question is high.

2.3. Water.

It is not possible to analyse in detail the various water requirements of different grassland and tree species and ecotypes. However, a few points have to be made which are of particular relevance to situations where trees and grasslands are either in intimate mixture or in close enough association that one may influence the moisture regime of the other (e.g. shelterbelts).

Under the same soil and air moisture, temperature and illumination regimes, different species and ecotypes transpire at different rates per unit leaf surface area. The average water consumption per gram of DM produced also differs between species; Larcher (1975) provided figures for the average number of grams of water transpired per gram of
DM produced for the following species:

- Millet (a C4 plant): 300g
- Rye (a C3 plant): 630g
- Beech: 170g
- Birch: 320g
- Larch: 260g
- Douglas-fir: 170g

Table 2.3 shows that different cultivars of the same species also have different water use efficiencies.

Plant growth is reduced by both excesses of water in the soil (through reduced oxygen concentrations which are essential for root respiration) and shortages of moisture. Long term moisture deficits are experienced in many pasture and forest regions of the world, and throughout the tropics moisture deficits are an important limitation to pasture production (Whiteman 1980). The extent to which moisture can be absorbed from the surrounding air is uncertain, though Louw (1972, quoted in Mount 1979) showed that a perennial desert grass (Stipagrostis uniplumus) varied in percentage moisture content over a 24 hour cycle, with c. 18% higher moisture content just before dawn when the relative air humidity was highest (see fig. 2.11).

Growth, photosynthesis and respiration are all affected by water stresses in the plant and are obviously interconnected, both through stomatal movements and carbohydrate metabolism. Generally water stress leads to a decrease in photosynthesis by reducing stomatal aperture (Bannister 1976); these conflicting demands for water conservation and continued photosynthesis are met in two ways: 1) stomatal transpiration control ensures that lethal water deficits do not occur and; ii) the
Table 2.3. Effect of different grasses, rainfall, and nitrogen levels on water use efficiency. (From Mott et al. 1977).

<table>
<thead>
<tr>
<th>Grass Type</th>
<th>1953 (1007 mm rain)</th>
<th>1954 (347 mm rain)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>N levels (kg/ha)</td>
<td>N levels (kg/ha)</td>
</tr>
<tr>
<td>Cynodon dactylon, Common</td>
<td>56  112  224</td>
<td>56  112  224</td>
</tr>
<tr>
<td>Cynodon dactylon, Coastal</td>
<td>6812  2896  1546</td>
<td>9738  5028  4336</td>
</tr>
<tr>
<td>Cynodon dactylon, Suwannee</td>
<td>2478  1431  803</td>
<td>1547  982  641</td>
</tr>
<tr>
<td>Paspalum notatum, Pensacola</td>
<td>1923  1104  692</td>
<td>1107  725  452</td>
</tr>
<tr>
<td>Digitaria decumbens, Pangola</td>
<td>2200  1321  870</td>
<td>3103  1945 1239</td>
</tr>
<tr>
<td></td>
<td>2249  1585  2240</td>
<td>2843  2513  3016</td>
</tr>
</tbody>
</table>

Fig. 2.11. The relation between the relative humidity of the air at various times of the day and the moisture content of a perennial desert grass Stipagrostis uniplumus. (Louw 1972, in Mount 1979).
plant can tolerate the development of relatively large deficits within its leaves (eg. *Acacia craspedocarpa*) (Bannister 1976).

Short term moisture stress can occur with daily fluctuations in high evaporative demand, such as on clear days during the middle of the day, when trees and some grasses and herbs can experience difficulty in maintaining turgor in leaves even though soil moisture may be plentiful. The guard cells may restrict transpiration (and \(\text{CO}_2\) uptake) until the plant water potential has been increased and the stomata open again.

However substantial amounts of water stored in plants can maintain transpiration in a plant for several hours (Monteith 1977). In trees, water conservation measures are not taken in all parts of the crown at once. The first and most prominent reduction of transpiration occurs in the shady parts of the crown and finally even the top of the leaves limit their evaporation. The rise in water potential in the sunny tops of trees is sharper than in shaded parts and these topmost leaves are preferentially replenished with water (Larcher 1975).

Plants or parts of plants in different physiological states vary in the degree of their drought resistance. Tolerance of dessication is usually lowest at the beginning of the new growing season; chloritic plants show little resistance to induced deficits and show a reduced ability to recover from these deficits (Bannister 1976). Table 2.3 shows that with the exception of "Pangola", increased N levels increased water use efficiency (Mott *et al.* 1977). In arid regions of India, it is known that adequate soil fertility helps to maintain a higher activity of plant enzymes and therefore production performance in wheat and pearl millet under conditions of water shortage and
temperature stress (Lahiri 1980). Table 2.3 also indicates that different species or varieties can alter their efficiency of water use to different extents with changing moisture availability: "Coastal" and "Suwannee" varieties of Cynodon showed greater efficiency during the dry year than during the wet year, while the reverse was the case for the other 3 grasses.

Shaded dwarf shrubs (and probably most pasture plants) are less able to resist the formation of deficits and more intolerant of low water-contents than plants in the open (Bannister 1976); this may be mainly due to the usually increased shoot: root ratio and to the larger and thinner leaves (increased specific leaf area) found in shaded plants. In the Gascogne Landes (S.W. France), trials with Festuca spp. growing under different degrees of shading showed a water-light interaction; while production doubled as shading decreased from 25% of full light to 45%, production only increased further with full light in years with normal precipitation (i.e. no drought) (Caquet 1980).

Humphreys (1981) also reported on the tropical grass Panicum maximum var. trichoglume showing a reduced net photosynthesis rate while under a certain degree of moisture stress with a maximum photosynthesis level occurring at a lower illuminance.

Broadly plants either resist or avoid drought, though often the mechanisms involved for a species may include both means of adaptation.

Morphological adaptations in the aerial part of plants (cutinization, epidermal hairs, sunken stomata, folding or rolling the leaves) help reduce transpiration from the leaves. Leaves developed under conditions of poor water supply are as a rule smaller and more strongly subdivided, and have a smaller specific leaf area (Larcher 1975).
Several mechanisms enable plants to avoid drought stress: quick completion of the life cycle during the period when moisture is relatively abundant (for example annuals, or trees which shed their leaves); deep and extensive roots may tap water from deep down and enable water to continue to be transpired; some pasture species, such as *Brachiaria miliformis* in the tropics, become dormant at the onset of a moisture deficit (Lane 1980). The species which show drought tolerance are those which are able to tolerate the development of large deficits within their tissue.

The interactions between water status and other environmental factors on plant growth are complex; in general, given an adequate supply of soil moisture, plants increase their rate of transpiration with increasing temperature up to a certain point (more energy for vaporization and greater concentration gradient leaf to air), and similarly with increasing light intensity (resulting in higher leaf temperature) up to a point where leaf water deficit reduces turgor and stomata start to close. Lower air moisture content (greater potential gradient) also increases the rate of transpiration. A similar response occurs with increasing wind speeds if there is a reduction in the boundary layer resistance i.e. particularly if there is a high vapour pressure differential between the stomatal cavity and the ambient air. Canopy or leaf resistance (to water loss) decreases with increasing irradiation and increases with plant moisture stress (Kramer et al. 1979, Oke 1979, Sturrock 1975).

### 2.4 Wind

Wind affects plants in several direct and indirect ways. It
influences the moisture regime of plants by increasing the potential for evapotranspiration (see section 2.3); it can reduce plant temperature both when the rate of evaporation is increased and by forced heat convection from the leaf; as the surface temperature is decreased, it may therefore decrease the rate of transpiration if there is a reduction in the driving gradient for evaporation (Grace 1981, Rees et al. 1980). Leaves can be damaged by wind but compensating mechanisms (increased photosynthesis in intact tissues, increased leaf expansion rate of new leaves) may reduce the impact of damage on plant growth (Russel et al. 1979a); further the relative importance to the plant of the leaves which are most easily damaged will determine the extent of the impact of wind. For two grasses (Festuca arundinacea and Lolium perenne), the damage to leaves increased with wind speed (1 m to 10 m/sec), up to 10% of the leaf area being lost, but the loss was mainly confined to the older leaves (Russel et al. 1979b). Plants may be affected by wind to different extents depending on their growth habits, on their differences in leaf and stem flexibilities, and on the relative physiological importance to the plant of the leaves which are damaged.

Russel et al. (1979b) found that the mean relative growth rate of Festuca arundinacea and Lolium perenne decreased with increasing windspeeds; (1 to 10 m/sec. above the canopy); the decrease varied in extent for different parts of the plant and was most significant for leaf area. The reduction in leaf area ratio was too large to be balanced by the 15% increase in net assimilation rate found with increasing wind speeds. The low leaf area ratio was due to a fall in specific leaf area which showed an average reduction of 25% for both
species at the high wind speeds. A lower net rate of photosynthesis per unit weight also resulted, possibly because of reduced light penetration in the thicker leaves of the plants exposed to wind. With an increase in wind speed from 1 m - 7.4 m/sec. a reduction in leaf extension of up to 20% was found to occur. The ratio of roots to total plant weight was significantly greater at higher wind speeds.

In a controlled experiment, continuous shaking of F. arundinacea stems caused a 20% reduction in leaf extension rate, and therefore the reduction in leaf expansion and relative growth rate found with increasing wind speeds may be mainly due to a mechanical stimulus when the water relations are unaffected (Russel et al. 1979a, b.).

High wind speeds and turbulence may also flatten pasture plants and crops, thereby reducing productivity, particularly when the plants are tall. Such a situation may occur in sheltered situations where vegetation may be taller due to the effect of shelter and infrequent high wind speeds may therefore have a more damaging impact on the sheltered vegetation than on unsheltered vegetation.

Wind affects trees in broadly similar ways to grassland and crops - Rees et al. (1980a) found that Pinus contorta seedlings (of Long Beach provenance) had leading and lateral shoot extension reduced by 22% and 17% respectively with wind speeds increased from 0.6 m - 8.5 m/sec. in a controlled environment (wind tunnel). Furthermore, needle extension was reduced by 31% with wind speeds increased from 0.4 m - 7.0 m/sec. The bud temperature was reduced from 16.9 to 15.3°C at the high wind speed and is therefore unlikely to be a significant contributory factor to the decrease in needle and shoot extension. Again the mean action of shaking reduced the leading and lateral shoot
extension by 21% and needles of shaken plants were 10% shorter than the unshaken controls (Rees et al. 1980b).

In both experiments (wind tunnel and shaking) Rees et al. (1980a, b) found that the water potentials of the plants were less negative in plants which were shaken or exposed to winds; this may have been due to reduced leaf area and therefore less transpiration per unit of stem or per volume of soil, or to higher root to shoot ratios.

Different species and different ecotypes no doubt respond to increased wind speeds to different extents.

Strong winds also break trees and blow them over. Factors which affect the likelihood of windsnap, given a certain wind are: the extra weight which the crown may carry in the form of frozen snow or hoar frost, or leaves in the case of deciduous trees; the time over which and the degree to which the tree has been used to similar wind speeds. The overturning and breakage of trees will be affected by rooting depth (which is influenced by soil conditions such as the degree of waterlogging), rooting spread and the extent to which the tree has been used to exposure. Again species differences are important in the degree to which they are liable to break (eg. flexibility of stem) or blow (rooting depth, canopy resistance and flexibility to wind).

2.5 Conclusions.

Many of the investigations quoted in the previous 4 sections have looked at the influence of the relevant environmental parameters on plant responses under controlled environmental conditions (eg. artificial shade). They have attempted to minimize possible differences between the control and treatment plots in environmental
factors other than those specifically investigated. For instance Eriksen et al. (1981, 1982) with their trial which looked at the influence of shade on various growth and physiological responses of 6 tropical grasses and legumes, supplemented natural rainfall in the treatments with varying amounts of water by subsurface drip irrigation so as to compensate for the lower levels of water expected to be used and transpired in the shaded plots. Under field conditions however, altering one environmental factor influences other environmental factors both directly and indirectly. A reduction in light intensity may decrease plant surface temperature which may in turn decrease evapotranspiration rates and hence increase soil moisture concentrations; a reduction in wind may increase ambient air and leaf temperatures so that growth rates may be faster and transpiration losses higher leading to lower soil moisture contents; or it may result in a higher relative humidity resulting in lower transpiration losses.

However trees influence the light, wind, precipitation and temperature regimes as well as soil nutrient and moisture regimes (see Chpt. 4 and 5). In tree-pasture mixes, it is therefore the cumulative and interactive influences of the tree component on the various factors which influence understorey production which are important. Some tree-pasture mixes in a certain environment may result in cumulative negative influences on the understorey component: where trees reduce the soil moisture available to understorey plants, and if these species respond to shade by having a low root to shoot ratio, the influence of trees on the pasture is likely to be particularly detrimental. In other situations trees may influence some parameter adversely and others beneficially resulting in little difference in pasture response.
between sites with and without trees. Yet in other situations, the trees may influence a number of factors in a way which enhances pasture growth: fertility may be improved, temperature and high irradiance stress reduced.

When one takes into account the seasonal fluctuations in the value of forage, the differences in combined direct and indirect effects of trees over different seasons on pasture production become important. In situations where pasture harvesting and storage does not occur, a detrimental effect on the total annual pasture yields would be of little consequence to livestock production where the reduction occurs during times of surplus pasture production whilst no difference occurs at the times of the year when there is a shortage. On the other hand, if a reduction due to trees is during the dry part of the year or during drought years, then their significance is considerably greater. Similarly if there are reductions in yields in all seasons, the degree of the reduction may vary between seasons in which the feed value may differ.

The interactive influences of the various climatic factors on plant growth are highly complex but they need to be understood before explanations can be given for observed variations in plant responses which occur in tree/pasture mixes of different species and in areas experiencing different climatic regimes. Further if one is concerned ultimately with livestock production as a product of the understorey component of the system, it is an understanding of the effects on the pasture characteristics of most relevance to livestock nutrition which is important. A considerable amount of knowledge exists concerning the response of understorey plants to the various climatic parameters which
trees influence, but a lot more research needs to be done before one can predict the likely yield and quality responses of different species under various management regimes given various qualitative and quantitative changes in the climatic parameters influenced by trees.

The importance of intraspecific differences in the response to fluctuations in climatic parameters must be considered both when trying to explain variations in response between sites and when introducing exotic germplasm in agro-silvopastoral combinations.
CHAPTER 3

Climate and Animal Production

This study requires an investigation of the influence of climate on animal production since trees can exert an influence on climate (see chapter 4).

3.1 Direct effects of climate on animal production.

The environmental factors which influence an animal's thermal environment are wind, rain, solar radiation, long wave radiation, ambient temperature and humidity.

The deep body temperature of domestic stock has to be maintained within narrow limits which are specific to species and breed and normally occur in the range 37°C - 39°C. Fig 3.1 shows diagrammatically the relations between heat production, evaporative and non-evaporative heat loss and deep body temperature in a hypothetical domestic animal. The zone of thermal neutrality (CD in Fig. 3.1) is the temperature zone over which there is least thermoregulatory effort; it coincides with minimal material demand either for food to provide energy in the cold or for water for evaporative heat loss under hot conditions. The zone coincides broadly with the comfort zone and the zone for optimum production such as growth, milk yields, reproduction (rate of increase in product per unit of food and water consumption). Since outside the zone of thermoneutrality the climate can be of significant hindrance to animal production, it is worth outlining how an animal's thermo-neutral zone can vary.

The scale values and the temperature range between zones in
Fig. 3.1. Diagrammatic representation of relations between heat production, evaporative and non-evaporative heat loss and deep body temperature in a hypothetical domestic mammal. A, zone of hypothermia; B, temperature of summit metabolism and incipient hypothermia; C, lower critical temperature, CT; D, upper critical temperature of marked increase in evaporative loss; E, temperature of incipient hyperthermic rise; F, zone of hyperthermia; CD, zone of least thermoregulatory effort; CE, zone of minimal metabolism; BE, thermoregulatory range (from Mount 1979).
Fig. 3.1 depends on species, breed, age, plane of nutrition, acclimatization history and several environmental factors.

3.1.1 Livestock characteristics which effect the zone of thermal neutrality.

Different breeds and individuals have different ranges of thermal neutrality because of different inherent characteristics such as body size and shape, wool or hair length, piloerection capabilities, hair or wool and skin colour and therefore absorbance, subcutaneous insulation characteristics, peripheral vaso-constriction and vaso-dilation propencities, basal metabolic, sweating and breathing rates. For instance modifications of behaviour for temperature adaptation do not occur in European Cattle (Bos taurus) between about 2°C and 21°C, while the corresponding range for Brahman cattle (Bos indicus) lies between 10°C and 27°C (Mount 1979) (though there are wide variations within each type).

Young domestic stock have a more restricted range of thermal neutrality than adults; the zone is very restricted in the new born because the thermoregulatory mechanisms are not well developed and because of the high surface area to volume ratio. In young lambs the zone lies in the range 25°C to 30°C (Mount 1979). As the offspring grows, the reducing surface area to volume ratio and the increasing insulation raise points C and D (Fig. 3.1) respectively. Well fleeced adult sheep have low lower critical temperatures (C) of -20°C or even below.

The extent to which an animal is physically active alters the temperatures at which thermoregulatory mechanisms are set in motion. The extent to which an animal grows, or produces milk (change in metabolic rate) has the same effect, although these
activities are also partly associated with increased nutritional intake. Webster (1974) gives the following lower critical temperatures (C) for cattle of different production levels (Table 3.1).

Table 3.1 Heat production of cattle confined at thermoneutrality and at different stages of production (in housed conditions with a wind velocity of 0.16 m s^{-1}).

<table>
<thead>
<tr>
<th>Cattle type</th>
<th>Body weight (Kg)</th>
<th>Heat production (W m^{-2})</th>
<th>Lower critical temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calves newborn</td>
<td>35</td>
<td>100</td>
<td>+9</td>
</tr>
<tr>
<td>Veal calf</td>
<td>100</td>
<td>154</td>
<td>-14</td>
</tr>
<tr>
<td>Baby beef cattle</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 kg gain/day</td>
<td>350</td>
<td>144</td>
<td>-12</td>
</tr>
<tr>
<td>1.3 kg gain/day</td>
<td>350</td>
<td>155</td>
<td>-26</td>
</tr>
<tr>
<td>Dairy cattle</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2 galls/day</td>
<td>500</td>
<td>129</td>
<td>-24</td>
</tr>
<tr>
<td>4 galls/day</td>
<td>500</td>
<td>154</td>
<td>-32</td>
</tr>
</tbody>
</table>

With improved nutrition levels, the temperature of both points C and D are lowered since the metabolic rate is increased. The proportion of fibre in the diet is also important; a low fibre ratio, compared to a high fibre ratio of approximately the same net energy content, lowers body temperature and respiratory rate (Yousef et al. 1968) and therefore presumably raises the temperature of D as evidenced by the good yields at high ambient temperatures in Israel dairy herds with heavy concentrate and low roughage feeding (Bonsma et al. 1967).
With extended periods of exposure to a change in ambient temperature, and/or through other environmental stimuli (e.g. photoperiodism), animals can acclimatize to a certain extent to a different temperature range; the thermoneutral zone is thereby raised or lowered by, for instance, a change in coat thickness or colour.

When an animal's fleece is cropped each year, there is a great reduction in the thermoneutral zone due to reduced insulation. In sheep shorn to a fleece length of about 7 mm, the lower critical temperature can rise to 28°C and even higher for fleeces cropped even closer (Mount 1979); point D will also be lowered.

3.1.2 Environmental effects on the Thermoneutral Zone.

Table 3.2 provides an indication of how the lower critical temperature and the upper critical temperature of the thermoneutral zone are influenced by the more important environmental factors.
Table 3.2 Influences on C and D (Fig. 3.1) by various environmental factors and the operative mechanism through which the environmental factor operates. (+ = increased temperature; - = decreased temperature; brackets indicate that the increase or decrease are not likely to be significant).

<table>
<thead>
<tr>
<th>Environmental factor</th>
<th>Operative mechanism</th>
<th>C ambient Temperature</th>
<th>D ambient Temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind</td>
<td>reduced thermal insulation</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>increased surface humidity gradient</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>rain</td>
<td>lowered thermal insulation; convection</td>
<td>+</td>
<td>(-)</td>
</tr>
<tr>
<td></td>
<td>loss of energy; conduction</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td></td>
<td>surface evaporative heat loss</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>absolute air humidity</td>
<td>reduced humidity gradient</td>
<td>(+)</td>
<td>-</td>
</tr>
<tr>
<td>solar radiation</td>
<td>surface absorption</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>long wave radiation</td>
<td>gain (from ground, cloud, dark surfaces)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>loss to cool surfaces</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>hard surface</td>
<td>conduction heat loss</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>temperatures</td>
<td>(eg cold ground, water bodies)</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td></td>
<td>conduction heat gain</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>water ingestion</td>
<td>usually at lower than body temperature loss of energy through evaporation, faeces, urine</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>food temperature</td>
<td>cold</td>
<td>+</td>
<td>(-)</td>
</tr>
</tbody>
</table>
Usually a combination of the above environmental factors together alter the thermoneutral zone; as each type of domestic stock (breed, age, nutritional status, stage of pregnancy or lactation etc.) is influenced to a different extent by any one of these factors, because of the individual's inherent characteristics already described, any combination of such environmental factors can affect to considerably different extents their thermoneutral zone. Table 3.3 shows the estimated lower critical temperatures of a well fed beef cow with different combinations of environmental factors.

Through behavioural changes, livestock can however either mitigate or enhance the effects of any one or more of the above environmental factors in order to remain in the thermoneutral zone.

In cold environments, in response to wind, particularly when combined with rain, stock seek shelter from vegetation and/or topographic features so as to reduce the increase in lower critical temperature. Changes in posture and grouping behaviour can mitigate increases in the lower critical temperature. A considerable increase in upper critical temperature can be achieved in an environment subjected to intense solar radiation by seeking shade to reduce the solar radiation load and by adopting an appropriate body posture to maximise long wave radiation to the cold sky.
Table 3.3 Estimated critical temperature of a well-fed beef cow in different cold environments (from Webster 1974). (\(I_t\), tissue insulation; \(I_e\), external insulation).

<table>
<thead>
<tr>
<th>Environment</th>
<th>Net radiation ((W \text{ m}^{-2}))</th>
<th>Thermal insulation (\left(\text{o}^\circ \text{c m}^2 \text{ W}^{-1}\right))</th>
<th>lower critical temperature (\text{o}^\circ \text{C})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry, calm ((V = 0.4 \text{ m s}^{-1})) overcast</td>
<td>-10</td>
<td>0.25</td>
<td>0.29</td>
</tr>
<tr>
<td>Dry, calm, 8 h direct sunshine</td>
<td>+63</td>
<td>0.24</td>
<td>0.29</td>
</tr>
<tr>
<td>Dry, calm, 4 h sunshine, 16 h cloudless night</td>
<td>-68</td>
<td>0.26</td>
<td>0.29</td>
</tr>
<tr>
<td>Dry, windspeed 4.5 ms(^{-1}) overcast</td>
<td>-10</td>
<td>0.26</td>
<td>0.17</td>
</tr>
<tr>
<td>Overcast, raining, cool wet, windspeed 4.5 ms</td>
<td>-10</td>
<td>0.28</td>
<td>0.09(^{(3)})</td>
</tr>
</tbody>
</table>

(1) uncorrected for radiation exchanges.
(2) windspeed at 1 m height.
(3) extrapolated from measurements made with sheep.
3.1.3 Temperature stress and animal production.

Several aspects of animal production are affected by either heat or cold stress. Most of the data available on the effect of any climatic component leading to heat or cold stress have been derived from experiments in enclosures where specific climatic characteristics can be varied and the response of stock to such variation measured. However real grazing and management situations are so much more complex that it is not possible to integrate the results from controlled experimentation to predict accurately either the impact of changing climatic conditions on stock productivity or the value of any combination of measures which can be taken to improve the climatic environment - for instance by the provision of shade or shelter trees. Further the effects of the climate have to be integrated with those of nutrition and health status which may vary widely. Few data are therefore provided.

Heat stress.

As the environmental temperature rises above the upper critical temperature (D), stock can still maintain deep body temperature by increasing evaporative heat loss (which necessitates an increase in water consumption) either through increased breathing rate, sweating rate or both.

In the U.S., it is generally accepted that on average cattle increase their water intake by 100% or more as the temperature rises from 21°C to 32°C (McDowell et al., 1967). In Mali Pagot (1967) showed that under natural conditions with ad libitum water availability once a day, the water consumption can increase by over 200% between cooler "wet" periods and the hot dry period
for the N. Dema (Bos taurus) stock and by nearly 200% for Peuhl (Bos indicus) stock. He showed clearly however that factors other than temperature, such as air humidity and mean fodder moisture content also influence water uptake.

There is however a limit to the extent to which evaporative loss can maintain deep body temperature and further in many environments water availability is low at least at certain times of year, and therefore below that required for evaporative heat loss (Iousef et al., 1968).

Heat stress leads to reduced food intake, probably to reduced digestibility coefficients and absorption of metabolites from the intestine, and therefore to reduced growth rates (Hafez 1968, Singh et al. 1982). Milk production and quality is also depressed by heat stress. Webster et al. (1980) mentioned a study in which the average production of milk of New Zealand cows was 44% higher than that of their co-twins in Fiji, while the butter fat produced was 50% greater in the temperate climate even though the conditions of feeding and management were similar. In N. Oklahoma, McIlvain et al. (1971) found that Hereford calves with access to ad libitum water gained an average of 9.5 kg more each year when they had access to shade than calves under the same conditions of management except for the lack of shade (the average varied between years from 2 kg to 13.5 kg due to varying temperature and humidity regimes). The use of shades can also lead to better feed conversion (Preston et al., 1974).

A reduction in growth rate delays the onset of puberty in both males and females; heat stress is thought to have an important contributory influence on this major limiting factor in breeding of yearling heifers for beef production in the tropics (Webster et al., 1980).
The reproductive rate is considerably lowered by heat stress. Spermatogenesis is adversely affected in cattle by stress periods of as short as 8 - 12 hours leading to low conception rates; recovery to normal spermatogenesis takes 6 - 8 weeks of exposure to lower temperatures (Vincent 1972). Spermatogenesis is also reduced in sheep (Hafez 1968). In females, heat stress leads to an increased incidence of anoestrus and longer cycles of anoestrus (Sawyer 1979a). There is considerable evidence that the reproductive life of cows is also shortened (Webster et al. 1980). Conception rates are lowered in both sheep and cattle by heat stress at any time over a period immediately prior and subsequent to mating (Hafez 1968, Sawyer 1979b), Terrill 1968, Vincent 1972). Embryo survival and prenatal development is also reduced leading to considerably fewer and smaller offspring (Webster et al. 1980).

Offspring are more susceptible to heat stress and subsequent death due to the higher surface area to volume ratio. In N.W. Queensland, where neonatal mortality rates are high and cause a crippling loss to the sheep industry, Hopkins et al. (1980) found that pregnant Peppin Kerino ewes which were subjected to heat stress gave birth to lambs with a significantly ($P < 0.01$) lower mean weight of 2.3 kg compared to 3.4 kg for ewes not subjected to heat stress. Further the maturation of wool follicles was retarded in smaller lambs and subsequent insulation from heat and solar radiation was reduced; the wool yields were still lower than those from lambs from unstressed ewes up to 14 - 18 months after birth. (The stressed ewes were subjected to heat stress equivalent to that found under natural grazing conditions where for 6 months of the year mean monthly temperatures are 35°C or higher with high radiation loads and shade protection on
the vast plains is scarce). In field studies over 2 years, they found that for each °C increase in ewe rectal temperature over that of unstressed ewes, there was a significant reduction \( \text{P < 0.01} \) in lamb birth weights of \( 1.50 \pm 0.35 \) kg. Small lambs had a significantly reduced \( \text{P < 0.01} \) chance of surviving to mating. In the second year, the poor conditions of the grazings onto which the lambs were weaned led to half the lambs dying. Weaker and heat stressed lambs find it more difficult to suck and the ewe, particularly if heat stressed herself, may consequently show reduced mothering behaviour. Hopkins et al.'s (1980) investigations further revealed that the lambs panted heavily from 9 am until late afternoon; exhausted from thermoregulatory efforts they fell asleep in the cool of the evening and therefore many failed to suck during this critical period; the mothers may also take advantage of cooler conditions to graze.

**Cold stress.**

Tables 3.1 and 3.3 indicate that cold air temperatures alone are likely to have little detrimental effect on adult sheep and cattle except in the case of recently sheered sheep. Heat losses to cold ground, however, when stock are bedded on short grass can be extremely high (Gatenby 1977 quoted in Grace et al. 1979). The long wave radiation heat loss to a clear sky can be considerable \( \text{[Grace et al. 1979]} \) particularly for cattle, since the radiative temperature of a cloudless sky is often \( 20^\circ\text{C} \) lower than ambient temperature. Table 3.3 and fig. 3.2 do indicate however that for cattle and sheep it is the combination of cold with rain and wind together which require heat production, over and above that of basal metabolic rate, to maintain deep body temperatures. Even for a mature sheep with a full fleece of 100 mm, a cold wet windy
Fig. 3.2. Metabolic rate related to environmental temperature in British bred sheep with different fleece depths (1 mm, 7 mm, 100 mm) and exposed to "still air" (wind 0.1 m s\(^{-1}\)) or a wind of 7 m s\(^{-1}\) (25 km h\(^{-1}\)) (From Alexander 1974).
environment, with temperatures close to 0°C (often encountered for instance in British hill conditions in winter), can lead to a doubling of metabolic rate.

The increase in metabolic demand has to be met by increased food intake and or depletion of fat reserves, and ultimately of body protein. Often, as in the British hills in winter, and early spring the naturally occurring food availability and quality is low during the period of cold stress, and unless supplementary feed is given stock is considerably weakened over this period. The extent and seriousness of this loss of body condition depends on several factors: the condition of stock (fat reserves) at the onset of harsh weather, the severity of the weather over 24 hour cycles, the pattern of distribution of severe weather over a winter period, the availability of topographic and vegetation natural shelter and the extent to which the stock responds behaviourally (body posture, grouping behaviour, seeking of shelter) to different thresholds of exposure to cold stress. The dilemma faced by stock is well illustrated in a comment by an experienced flock master in the Scottish hills, who suggested that his sheep which graze on an exposed hill are in better condition than those in any other area, as they have no alternative to continued grazing, whereas those with shelter suffer more from reduced grazing than they would from exposure (Doney et al. 1964). However complications with differences in nutrition quality may occur, as the best pastures (Agrostis spp., Festuca spp.) only raise the breaking action of the winds to 5 - 8 cm above the ground, while in Molinia and Nardus pastures (poorer quality) the height at which the wind force is negligible approaches that of the full height of sheep 25 - 50 cms.
Heather (*Calluna vulgaris*) provides even better shelter. Certainly detailed studies of sheltering behaviour under varying degrees of climatic stress in natural situations show that hill sheep (e.g. Blackface ewes, Welsh hill sheep) do increasingly seek shelter from vegetation and topographic features if these are available as cold stress (wind, rain) increases (Hunroe 1961, 1962, Griffiths 1962, 1967, HFRD 1964), even if this means moving from a better onto a poorer quality pasture. However, British hill sheep, particularly Blackface have well defined and limited home ranges which restrict their choice of response to cold stress. A further behavioural complication occurs with territorial sheep in the assessment of exposure and means to mitigate it: the less competitive ewes and particularly gimmers appear to be handicapped in grazing competition with older ewes; they also suffer a great loss in body weight over the winter (Russel 1964). Different breeds respond behaviourally in different ways; in severe storms in S.E. Southern Australia, Merino and Merino crossbreeds moved with the wind even out of shelter downwind onto more open country (Geytenbeck 1962).

Cold stress alone in British hill conditions reduces ewe body weight by 2 - 3 kg on average but this can be much greater in severe winters. The rate of loss in weight is rapid during the early part of the stress period, and is soon reduced as the lower body weight comes into a new equilibrium with increased requirements (Russel et al. 1969); they suggest that the differences in *ad libitum* feed consumption between Blackface sheep in sheltered pens and sheep in exposed pens may be of the order of up to 15%.

However the important factors in animal productivity in
grazing systems in which the returns depend on the sale of lambs and ewes in the autumn, after the best period for growth, are more related to the reproductive performance of the flock - i.e. number of animals sold in the autumn as a proportion of the number of animals kept over the winter. One of the key limiting factors in hill stock productivity in UK is lactation; it influences the growth rates of the young before weaning and therefore the ability of the mother to regain full breeding weight and resume oestrus.

In extensive systems such as under many British hill conditions, the proportion of loss of ewes, hill cows and calves can be significant in severe storms, when these occur towards the end of the winter and the preceding period has been harsh. Late snow storms which smother vegetation, thereby reducing the possibility of feeding, and which bury stock in sheltered snow accumulation areas are particularly serious.

In ewes the onset of oestrus can be delayed by cold stress (Doney et al. 1981). The ovulation rate can be significantly reduced by over 30% in Blackface ewes even if these are in good body condition (Griffiths et al. 1970). There is also evidence that early embryo mortality increases with cold stress in Blackface ewes (Griffiths et al. 1970) and in Welsh mountain ewes where one foetus may die in ewes carrying twins (Lucas et al. 1975). The magnitude of the effect of these factors is likely to depend on the critical timing of the stress, both prior and subsequent to mating. The critical premating period is the week immediately prior to mating (HFRO 1979) and although Griffiths et al. (1970) found that most of the early embryo loss occurred on or about day 14 or 15 post mating, Doney et al. (1981) suggest that the critical post mating period lasts 30 - 40 days.
The impact of cold stress on subsequent stages of pregnancy up to parturition probably acts mainly through increasing the metabolic demand for heat production which reduces the energy available for foetal development; such effects are therefore difficult to dissociate from nutritional influences. The effect of the reduction in the fat stored subcutaneously (by c. 8.5% in general hill situations—HFRO 1979a) on the subsequent insulation efficiency of the ewe, particularly in wet windy weather when the fleece insulation is significantly reduced, is not documented. The energy requirements of a ewe carrying a single lamb immediately before lambing are about double that of a non pregnant ewe, while a ewe carrying twins has a requirement of about $2\frac{1}{2} - 3$ times that of a non pregnant ewe (Russel et al. 1977) and as these requirements are very seldom if ever met, the effect of the further burden of climatic stress late in pregnancy is significant. The mortality of ewes is highest in the last month of pregnancy (HFRO 1967).

The foetal growth rate is reduced by poor energy (and protein) availability which leads to low birth weights. Although a reduction of 25% in energy availability from full requirements reduces lamb birth weights by less than 10% in Blackface ewes (of little consequence), the shape of the response curve of the lamb's birth weight against energy intake indicates that any further lowering of the level of intake quickly leads to such reduction in lamb birth weights that their survival is prejudiced (HFRO 1979).

The effect of cold stress on the survival of lambs and on their subsequent growth rate is influenced through a whole range of interacting factors which are dependent on the ewes and lambs. Bystokia (choked lambs due to lengthy parturition) is of higher
incidence in weak ewes (Bannatyne 1977). The smaller and the weaker the lamb, the more it is susceptible to cold stress; its ability to suck is reduced (Russel et al., 1977) and cold stress further reduces this ability - an important contributor to lamb deaths in the U.K. hill and upland situations (Slee 1977) and in the cooler and wetter parts of Australia (Alexander et al., 1961).

A weak mother under stress is also likely to show reduced mothering attention, further reducing the likelihood of lamb survival (HFRO 1979). During early lactation, the grazing is usually inadequate, and as the ewe uses dwindling body reserves for milk production, it is easy to see why ewe mortality is also high (and therefore lamb mortality) during the first month of lactation (HFRO 1967). Ewes which have been exposed to considerable exposure during pregnancy have little milk at the onset of lactation (HFRO 1979, Robinson et al., 1969). Although lamb growth is determined by milk production, which in turn is dependent on the ewe's feed availability, weak lambs through low initial demand may depress milk production and their weaning weight is likely to be even lower. Independently of nutrition and body condition it is likely that cold stress reduces milk production generally and this is known to happen in cattle (Mount 1979). In British hill ewes, cold east winds in the spring can be particularly damaging to milk production, but the role of their indirect effect through the drying up of pastures is uncertain (Munroe 1961). The time of initiation of grass intake is postponed and the rate of expansion of intake is reduced in lambs with small growth rate, thereby reducing their weight at sale and therefore the financial returns. Nutritional and climatic differences affecting growth during the juvenile period may have a significant effect on sub-

Throughout lactation, a smaller and weaker lamb is more likely to succumb to cold stress, as a greater proportion of the milk and body reserves have to be utilized for heat production rather than growth. Fig. 3.3 shows heat loss in lambs with varying combinations of climatic factors. Certainly field studies on the extent and the cause of death in lambs both in the British hills and uplands (E.S.C.A. 1977, Houston 1974) and in other parts of the world with similar climates at lambing time, such as the cooler parts of Australia (West and South West Australia, New South Wales) (Alexander et al. 1961, Alexander 1962, Watson et al. 1968, Egan et al. 1972, Lynch et al. 1980) show clearly that cold stress (usually wind with rain) is the major cause of lamb mortality. The depletion of energy reserves is the cause of most deaths in lambs, starvation being the main factor involved.

The losses in sheep due to cold stress after shearing can also be significant (Geytenbeck 1962, Hutchison 1968). In one bad year in the S.E. of South Australia, Geytenbeck recorded 8.3% of sheep shorn to have died due to strong winds associated with rain.

3.2 Indirect effects of climate on animal production.

The indirect effects of climate on animal production are numerous.

Disease

There are at least three ways in which climate indirectly affects animal production through increased disease susceptibility.

1) Animals weakened by heat or cold stress are more likely to succumb to infection. Hypomagnesemia (a non infectious disease)
Heat loss (KCal. M\(^{-2}\) HR\(^{-1}\))

Wet, no wind.
Dry, no wind.
Wet wind.
New-born wet wind.
Dry wind.

a) Fine coats

-60 -40 -20 0 20 40

b) Hairy coats

-60 -40 -20 0 20 40

Ambient temperature (°C)

Fig. 3.3. Heat loss due to wind and evaporation at various ambient temperatures in lambs with fine coats (a) and lambs with hairy coats (b). The dotted lines are extrapolations of these lines, or represent conditions under which very few results were obtained. Few results were obtained at low temperatures on wet lambs with hairy birthcoats. (From Alexander 1962).
in hill cows is more serious in severe winters (Blaxter 1969).

ii) The climatic conditions themselves influence the suitability of the environment for disease proliferation. For instance in New Zealand, facial excema and liver damage in sheep seem in some way to be related to soil and grass temperature as well as ambient moisture levels (Drew Smith et al. 1965). In the tropics and sub-tropics, the moist conditions prevailing around watering points which are associated with concentrations of cattle can lead to high concentration of pathogens. The incidence of head flies in sheep and mastitis in cattle is increased during warm weather in the British Isles where humidity is high.

iii) Unfavourable climate may increase the likelihood of the concentration of stock in more favourable areas (near shade, shelter or water). The concentration of stock may through excessive fouling enable a build up of parasites (Webster et al. 1980, Borissow 1962).

Pasture utilisation.

Because of uneven spacial distribution of inclement climatic environments, which makes stock concentrate in some areas, there can be a reduction in pasture productivity in the areas of concentration with unutilized grounds further away; this leads to an overall lower stock production than could be maintained by more even grazing (Munroe 1961, McIlvain et al. 1971, Williamson et al. 1978).

Pasture quality and quantity.

The effect of climate on plant production has already been discussed.
3.3 Conclusion.

The complexities of detrimental direct and indirect effects of climate on animal production are such that it is very difficult to maintain a clear picture of its effect on overall animal performance in its total environment. Much research tends to investigate very narrow aspects of the impact of specific climatic factors on specific aspects of animal performance; although such investigations are important, they usually fail to provide the agriculturalist with a realistic picture of the trade off between animal performance, the role of supplementary feed or water and measures, such as the provision of tree shelter and shade, which can improve the climatic environment of the stock. It is also likely that agriculturalists are completely unaware of the importance of the contribution of temperature stress at least on some aspects of animal production.

Nevertheless, in general terms, it seems clear that the provision of shelter, if carefully located, should improve the nutritional status of animals which are subjected to "cold" stress thereby improving production. Further, at specific times of year (e.g. mating, parturition) the role of shelter would seem to be beneficial whatever the nutritional status of the stock. The same would seem to apply to heat stress and shade provision.

The extent to which heat and cold stress occurs and is reflected in influences on growth and production and reproduction efficiency is however breed specific and considerable genetic variation can also occur within populations of the same breed (e.g. for cattle in Queensland, Turner 1982). Although measures can be taken to alleviate temperature stress, the magnitude of the differences in livestock productivity which
these measures may cause in different areas is unpredictable; this is particularly so when non climatic factors (e.g., nutrition, water availability, steepness of terrain) which have a bearing on temperature stress may also differ between areas.

The extent to which trees can provide some control over the animal's climate is discussed in Chapter 4.
The Influence of Trees on Microclimate

Chapters 2 and 3 outlined that even small differences in climatic conditions may have a significant influence on plant or animal production, particularly at sensitive points on the organism's response curve to a climatic factor. It is therefore important to be aware of the extent to which trees can influence a microclimate - even when only to a small extent - so that the best association of trees with pasture and livestock can be created by increasing their positive and reducing their negative climatic influences.

Although there is an interrelationship, to a greater or lesser extent, between the effects of trees on the light, temperature, moisture and wind microclimate, it is easier to deal with these separately. Light is dealt with first since the other factors affect this climatic parameter to a limited extent while light itself affects significantly at least the temperature regime. Wind is tackled next since, on a microscale, temperature and moisture regimes affect wind little while the reverse influence is significant. Lastly moisture and then temperature are considered. An attempt is made to look at the effects of trees on these microclimatic factors for two broad tree - pasture combinations: pastures growing next to blocks of trees and pastures growing in intimate mixture with trees.

4.1 Light.

It is easy to predict that with increasing tree crown cover,
the total daily amount of light reaching plants in the understory decreases. Most investigations which have looked at pasture production under or close to trees and attempted to relate the response to various microclimatic factors have either omitted to account for tree influences on the light regime (e.g. Farnsworth et al. 1976 for a *Pinus radiata* forest farm plantation in New Zealand), or have given an average light transmission for either the day or for certain times in the day.

An open Eucalypt forest (mean density of 96 stems ha$^{-1}$) in S.E. Queensland was said to have a minimum light penetration of 72% (maximum projected crown cover 55% and approximately 50% proportion of light intercepted in the canopy) (Cook et al. 1977). Similar studies elsewhere gave the following averages for incident light in proportion to that in the open when trees were in full leaf: 45% under sparse mesquite trees (*Prosopis juliflora* Swartz D.C.) in Arizona (Tiedemann et al. 1977); 50% under 20 - 23 year old coconut palms (9.1 x 9.1 m spacing) in Western Samoa (Reynolds 1978): 25% and 37% for closed and open natural woodland respectively near Fort Victoria (Zimbabwe) (Kennard et al. 1973). Anderson et al. (1979) near Perth (Australia) described the light regime of a pasture under 15 year old *Pinus radiata* (mean density of 261 stems ha$^{-1}$ pruned to 6 m height) as having "35% of the ground area shaded at noon at the end of July". Steel et al. (1974) in Bali, found that 30 year old coconut palms (10 - 12 m spacing) had the following mean light transmissions on clear or sparsely cloudy days (based on 175 measurements over 2 days): 77% at 900 hours, 88% at 1000, 80% at 1200, 66% at 1400 and 61% at 1500 hours; they do however state that shaded patches often received only 10% transmission, but shading at any point was intermittent.
according to wind movement of the palm canopy and to changes in the sun angle. Many such reports which refer only to spacing between stems or to stocking density are of little use to others who may wish to extrapolate to situations with other species, since canopy cover and row orientation are also likely to be fundamental in their influence on light regimes.

It should be clear however from chapter 2 that the net photosynthesis response of pasture plants can be markedly different between exposure to for instance a constant 50% light transmission, and an average of 50% with fluctuations varying between 10% and 90% of full light intensity. Further, variations in light quality may considerably influence physiological processes and therefore production. Light is an important ecological factor which can differ markedly in direction, intensity and quality, particularly in the understorey of trees; one has therefore to consider both light quantity and quality and their daily and even very short term fluctuations.

It is not possible to provide here a comprehensive treatment of the subject of short wave radiation regimes within or close to tree canopies. The subject has been partly dealt with by Allen (1974), Allen et al. (1976), Anderson (1966, 1971), Charles-Edwards et al. (1976), Clifford Evans (1966), Geiger (1965), Hatfield (1974, 1975), Jarvis et al. (1975), Lee (1978), Miller et al. (1971a,b), Monteith (1973), Nair (1979), Norman et al. (1971), Plucknett (1979), Reifsnyder et al. (1965) and Ross (1975). Nevertheless it is necessary to outline some of the factors involved and a few examples will show how important these can be.

4.1.1. Incidence of short wave radiation on the earth's surface.

It is first important to understand how the quantity and quality of radiation reaching a tree canopy varies with time of year, time of day, weather and other factors since the proportion of light intercepted by tree canopies varies with the angle of
the sun and the weather (see section 4.1.2 - 4.1.4).

There are two main types of short wave radiation (300 - 3000 nm) reaching the earth's surface (both of solar origin):

i) direct solar radiation (solar beam) (solar constant = c. 1360 - 1400 Wm$^{-2}$ or 1.94 - 2 cal cm$^{-2}$ min$^{-1}$);

ii) diffuse radiation (skylight and light transmitted through clouds).

The amount of direct solar radiation reaching the earth's surface depends on several factors: the angle of the sun in the sky determines the amount of atmosphere through which the sun rays have to travel; the atmospheric conditions (water vapour content, dust particles) determine the partitioning of solar radiation into energy which is absorbed or scattered and energy transmitted unaffected to the earth's surface. The atmospheric constituents selectively absorb different wavelengths. Ultraviolet ($<400$ nm) and lower frequency infrared ($>750$ nm) radiation are selectively absorbed by the atmosphere. As the scattering efficiency by the atmosphere is proportional to $1/\lambda$, blue light (400 nm) is scattered c. 9 times more efficiently than red light (700 nm) (Monteith 1973); the lower the sun is in the sky, the poorer in blue light in proportion to red light the direct radiation is. For practical purposes, 50% of short wave radiation is in the visible spectrum or broadly photosynthetically active radiation (PAR). On a cloudless day, direct solar beam accounts for 75 - 85% of total short wave radiation while diffuse sky light accounts for the remaining 15 - 25%; however diffuse sky light contributes a greater proportion of PAR since atmospheric absorption and scattering are greater in the wavelengths outside PAR (the fraction of PAR to total diffuse radiation is 0.7 to 0.8) (Fig. 4.1).
Fig. 4.1. Spectral distribution of total solar radiation (upper curve) and direct solar radiation (lower curve) calculated for a model atmosphere. Solar elevation is $30^\circ$ and precipitable water is 21 mm. The shaded area represents the diffuse flux which has maximum energy per unit wavelength at about 0.46 $\mu$m (from Monteith 1973).

Fig. 4.2. Solar irradiance on a cloudless day (16/7/1969) at Sutton Bonington ($53^\circ$N, $1^\circ$W); St total flux, Sb direct flux on horizontal surface; Sd diffuse flux. Full line from measurements; dashed line extrapolated. (From Monteith 1973).
The thickness and spacial distribution (\% of sky covered) of cloud affects short wave radiation quality and quantity. Water vapour absorbs in the infra red spectrum thereby increasing the proportion of PAR to total short wave radiation reaching the earth's surface, but the spectral distribution of PAR is little affected by cloud. Allen et al. (1976) quoted the ratios of radiation values at 400 nm to those at 700 nm as 3:1, 2.4:1, and 1.8:1 for clear, scattered cloud and hazy conditions respectively for diffuse radiation near Ithaca, New York. A thin cirrus cloud can allow more than 70\% of the flux to reach the surface, while deep stratus clouds can reflect as much as 70\% of incident sunlight, absorb 20\% and therefore leave 10\% for transmission to the surface. However thin broken cloud can increase the incidence of energy to any one point as long as beam radiation is not obstructed, since the diffuse flux is increased; the total irradiance can exceed the flux found beneath a clear sky by 10\% when a few cumuli are present. On average, the diffuse radiation from "clear sky" tends to be stronger nearer the horizon than at the zenith, while under a heavily overcast sky, the diffuse radiation is about 3 times greater at the zenith than at the horizon (Monteith 1973).

The incidence of potential PAR reaching a particular point on the earth's surface over a day is dependent on the daylight and sunlight hours, the variation of sunlight intensity over the day period due to changes in solar declination (varies with latitude and time of year), due to the angle of the receiving surface in relation to the sun's rays, due to the extent of sky occlusion by topographical features and to the albedo of these surfaces.

At any time, a surface receives directly from visible sky sources in which the sun is shining:
\[ \text{St} = \text{Sd} + \text{Sp} \sin B + \text{Se}, \]

where \( \text{St} \) = total solar irradiance, \( \text{Sd} \) = diffuse component of radiation from the sky and clouds, \( \text{Sp} \) is the direct component of irradiance on a plane surface perpendicular to the solar beam at elevation \( B \), \( \text{Se} \) is the incoming shortwave radiation reflected from adjacent portions of landscape (Monteith 1973, Lee 1978). The magnitude of \( \text{Sp} \) depends on many of the factors mentioned above and varies with solar altitude as shown in Fig. 4.2 (Formulae are available to calculate potential \( \text{Sp} \) for any location at any time Monteith 1973, Lee 1978). Fig. 4.3 shows the variation in potential insolation at the solstices for 3 latitudes, and Fig. 4.4 shows the seasonal variation in potential insolation at various latitudes in the northern hemisphere. The variation in daily potential insolation (Fig. 4.4) is therefore due to the variation in instantaneous flux density of potential insolation (Fig. 4.2) and to the seasonal variation in day length as a function of latitude.

The influences of slope and aspect are illustrated in Fig. 4.5. In spite of a smaller flux at noon in summer on north facing slopes, the total radiation for the day (area under the curves) is greater on the north \( (991 \text{ ly}) \) than on the south \( (980 \text{ ly}) \) slopes. At the summer solstice the potential daily total insolation at latitude \( 30^\circ \text{N} \) on a northern slope exceeds that on a southern slope by 3 to 28\% for slope inclinations of 10 - 100\%. At \( 40^\circ \text{N} \), the daily totals are virtually identical for all slope inclinations, while at \( 50^\circ \text{N} \) the relationship is approximately the reverse of that at \( 30^\circ \text{N} \) (derived from Frank et al. 1966). At lower latitudes, where daily totals of potential insolation can be much greater on north facing slopes during midsummer, south facing slopes or sides of trees/bushes may...
Fig. 4.3. Variation of potential insolation with true solar time at the solstices for latitude $\phi = 0^\circ$, $45^\circ$ and $90^\circ$. (From Lee 1978).
Fig. 4.4. Seasonal variation of potential insolation at various latitudes in the Northern Hemisphere. (From Lee 1978).
Fig. 4.5. Potential insolation on 30% north facing slope (dashed lines) and South-facing slope (solid lines) at latitude $\phi = 40^\circ$ N. (From Lee 1978).
be more favourable sites for growth, particularly if moisture is limited at this time.

4.1.2 The impact of trees on the incidence of shortwave radiation.

The light regime of the two broad tree - pasture associations are considered in sections 4.1.3 and 4.1.4. First it is necessary to outline how short wave radiation is altered, quantitatively and qualitatively by trees.

**Leaves and needles.** Individual leaves and needles partition short wave radiation into absorbed, reflected and transmitted radiation. Lee (1978) indicated how the leaves of different species can partition radiation in different ways (transmissivity $t$, reflectivity $r$, absorptivity $a$ - coefficients):

<table>
<thead>
<tr>
<th>Species</th>
<th>$t$</th>
<th>$r$</th>
<th>$a$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Locust ($R. \text{ pseudoacacia}$)</td>
<td>0.26</td>
<td>0.35</td>
<td>0.39</td>
</tr>
<tr>
<td>Ash ($F. \text{ pennsylvanica}$)</td>
<td>0.18</td>
<td>0.31</td>
<td>0.51</td>
</tr>
<tr>
<td>Alder ($A. \text{ rugosa}$)</td>
<td>0.21</td>
<td>0.25</td>
<td>0.54</td>
</tr>
</tbody>
</table>

However the angle of the leaf or needle in relation to the incident radiation alters the partitioning. Further the absorptivity, transmissivity and reflectivity of leaves varies significantly for different wavelengths (Fig. 4.6). The situation is similar in conifer needles as far as reflectivity is concerned but since transmissivity is very small in the visible spectrum, absorption is higher (Jarvis et al, 1976).

Several factors alter the partitioning. Leaf reflection is generally greater in drier habitats. Reifsnyder et al. (1965) gave average reflection of desert species leaves of 0.27 and for irrigated species 0.14. Infrared reflection is thought to decrease
Fig. 4.6. Transmissivity, reflectivity, and absorptivity of a typical hardwood leaf. (From Lee 1978).
with altitude and Reifsnyder et al. (1965) quoted figures for alpine fir needle reflection of 0.82 at an altitude of c. 700 m and 0.55 at 1500 m. Soil fertility, through its effects on leaf colour, and leaf age also affect reflection. The position of the leaves or needles in the canopy is also important. Leaves in the lower part of canopies of trees growing at reasonable densities are usually thinner and have a larger surface area; their absorptivity is therefore probably lower and their transmissivity higher than leaves in the upper parts of the canopy. In conifers, the same response occurs (Fig. 4.7) but in addition, in many species, the needles change from an erect position to a more horizontal position (Leverenz et al. 1980) thereby increasing the absorptivity of light (and the light extinction coefficient).

There are no major differences between broadleaves and conifers in their impact on the spectral composition of shortwave radiation, nevertheless, the depletion in the blue range is smaller in conifers, while they enrich rather than deplete in the red wavebands (Jarvis et al. 1975).

**Trees.**

Because of multiple internal reflection, which is particularly high in conifers between needles, the effect of the foliage of a tree on short wave radiation is basically to enhance both quantitatively and qualitatively the influence which an individual leaf or needle has. It is therefore the leaf area index, the spatial organization and orientation of the different leaves and their different morphological characteristics within the canopy which influence the light climate around and near trees.

The stems, branches and twigs of trees also reduce the incidence of light on the ground. Reifsnyder et al. (1965) reported on studies in North America, Germany and Britain where leafless hardwoods
Fig. 4.7. Specific needle area as a function of location in the canopy. (From Oker et al. 1981).
reduced the amount of light reaching the ground by 20 - 74%.

However the sun during the winter is low in the sky and therefore daily interception by tree trunks, branches and twigs over the summer is lower than the above figures. Nevertheless interception by "wood" is significant. In most species energy intercepted by "wood" is as the albedo is low (except in light barked species such as _Betula_ spp.) and transmission is zero.

4.1.3 Light regime adjacent to blocks of woodland.

The influence of a block of woodland (e.g. a shelterbelt) on incident short wave radiation upon adjoining pasture depends on several factors.

The block of woodland reduces the incoming diffuse sky and cloud radiation by the amount of sky which is obstructed from view.

The lengths of shadow to direct beam radiation and the time over which the shadow persists vary widely with the slope, latitude, time of day, time of year, height of the trees and orientation of the barrier and can be worked out according to geometric principles. Essentially in the northern hemisphere, north of the tropics, the northern side of woodlands receive decreasing amounts of total daily beam radiation with increasing slope angles to the north and as days are away from the summer solstice. However between the equinoxes and the summer solstice, northern edges receive low intensity solar radiation (sun low in the sky) in the morning and evenings.

The evaluation of incident radiation on Southern edges is complicated by a series of factors. The reflection of direct beam radiation from the woodland edge back to the pasture depends
on the species composition and on the roughness of the forest edge. The total daily incident solar radiation is therefore increased between the winter solstice and the equinoxes; the extent to which it is higher for any area of pasture near the edge than for areas away from the forest edge between the equinoxes and the summer solstice depends on the difference between the reduced direct beam radiation in the morning and evening and the increase in radiation due to reflection from the stand. However as reflected radiation is spectrally altered there are qualitative differences in the incident reflected radiation which make the evaluation of its impact on the pasture difficult. Nevertheless, it is known that the albedo of pasture can increase from 20% to 40% as one gets closer to a stand, since the albedo of the pasture increases in the wavelengths selectively reflected by the stand (Geiger 1965).

East and west edges receive similar solar radiation levels unless there is a regular pattern of change in cloudyness during the day. Rosenberg (1974) suggested that on a full day basis, the difference in radiation balance between areas near to or distant from the east or west sides of a woodland may be negligible since an area shaded in the morning receives additional reflected energy in the afternoon; however in terms of the difference in PAR balance and phytochrome stimulating wavelengths (far red) Rosenberg's suggestion is not likely to be correct.

Between the Tropic of Cancer and the equator, the incidence of radiation close to woodland depends on which side of the equinoxes the period lies; however only areas close to the woodland are affected since the sun is never low in the sky for long periods.

The proportions of incident PAR and far red wavelengths (stimulating phytochrome) to total amounts of radiation on pasture
close to woodland are not the same as those away from woodland for reasons mentioned in this section and in Section 4.1.1 (Fig. 4.8d).

4.1.4 Light regime in intimate mixtures.

A hemispherical photograph taken from ground level looking upwards (Fig. 4.9), helps to reveal how the various light components contribute to the light regime under a canopy.

The proportion of total diffuse or skylight radiation which reaches the understorey unaltered by leaves depends on the amount of sky which is not obstructed from view and therefore depends on the percentage crown closure and the LAI of the crowns. The location of clear areas in the sky hemisphere and the extent of cloudiness determine the flux of total diffuse radiation and the PAR flux (Section 4.1.1).

The amount of light which reaches the ground as diffuse radiation by reflection or transmission of leaves and other organs depends on the distribution of leaves in relation to incoming radiation and the solar track and to the leaves' angle in relation to the radiation. The fraction of PAR to total such radiation is only 0.2 (Monteith 1973) and the more leaves the radiation is transmitted through or reflected from, the more diffuse and the richer in infrared it becomes in proportion to visible radiation (Fig. 4.8c). (The fraction of PAR is 0.7 - 0.8 for radiation from blue sky, 0.5 for radiation from clouds). The higher above the ground the canopy lies, the smaller the leaves and the more even the distribution of leaves within the canopy, the smaller is the variation in diffuse light over space at ground level.

The incidence of direct beam radiation on the understorey varies with the percentage area of the sky hemisphere obstructed
Fig. 4.8. Spectral photon fluence rate distributions of natural global radiation under various terrestrial conditions; a) mid-day, clear skies; b) sunset, clear skies; c) under a vegetation canopy; d) on the shaded side of a hedgerow; f) moonlight (x10). (From Smith 1981).
Fig. 4.9. Hemispherical photograph of a stand of *Pinus sylvestris* (3 - 4 m apart; 18 - 21 m high) with solar track diagram for 52° 13' N. Roman numerals = month in the year; arabic numerals = time of day. (From Anderson 1966).

Note that in winter months direct solar radiation does not reach the understorey.
by canopies and according to the relation between the canopies' distribution and the solar track (and therefore with latitude, time of year, time of day, slope angle and orientation). From chapter 2 it can be said that there are 4 main aspects of the direct radiation regime below a canopy which may be important to understorey production (affecting PAR, phytochrome, air temperature, leaf and soil temperature, and moisture regimes):

i) the total daily radiation input over the day;
ii) the daily distribution of radiation of different intensity;
iii) the short term fluctuations in radiation intensity;
iv) the spectral composition of light at any one time.

While crown closure, in combination with crown depth is probably the most influential factor in determining total short wave radiation input, it is difficult to measure these characters. Reifsnyder et al. (1965) referred to several investigations, where stem density (summation of DBH in cm ha$^{-1}$) gave a good correlation with solar radiation transmission; stem density decreases with thinning, a decrease compatible with the resultant increase in light intensity, while basal area gives little weight to small trees and continues to increase as trees age (usually more light is found to penetrate the understorey as trees age after canopy closure). The correlation between light intensity and stem density is considerably improved by considering the size of the crown (e.g. small sized crown, Western Larch; large sized crown, Grand fir), and in particular crown depth.

The slope of the curve describing the increase in light transmission with decreasing stem density is initially steep and then levels off. Reifsnyder et al. (1965) quoted a Russian study on pine where the removal of 21% to 27% of the trees (17% to 24% of the basal area) increased light intensity by 3 to 4 times that...
in the unthinned plot. A detailed model of light absorption (Charles Edwards et al. 1976) by a hedge apple orchard with rows at different spacing (width of canopy kept constant at 1.8 m, clear trunk height 0.4 m and canopy height 1.6 m, at the summer solstice at latitude c. 50° N) also indicated that the amount of light transmitted shows such a relationship with crown area (Fig. 4.10a).

The time of day when varying intensities of radiation reach the understorey again depend on canopy density and with the spacial distribution of the canopies. A random distribution allows least light to get through the canopy (Allen 1974). With trees randomly distributed, the lower the density, the more the vertical distribution of the crown influences the spacial distribution of radiation on the ground, and its timing. A unit volume of canopy close to the ground allows some ground area to receive greater amounts of direct radiation and for longer periods than other areas, and only at high latitudes (in summer) will any area of ground be insolated more than once a day - the periods of insolation are therefore long. As the same unit volume of canopy is either raised above the ground (e.g. stem pruned trees) or as it is redistributed into a narrow tall crown (e.g. tall trees heavily lopped close to the stem), the total daily insolation on the understorey is likely to be more evenly distributed spacially; further each area of ground is likely to have its total insolation distributed over a number of periods of varying lengths.

If the trees or shrubs are not randomly arranged, the orientation of the rows influences both the total daily amount of insolation reaching the understorey and its timing. The vertical distribution of canopy volume also influences the distribution of light as mentioned above. At 50° N at the summer
Fig. 4.10. The effect of varying the spacing between north-south apple orchard rows on daily integrals of absorbed (by the apple trees) radiation, expressed (a) per unit ground area and (b) per unit row length. ——— total radiation; ——, direct beam radiation. (From Charles-Edwards 1976).
Charles-Edwards et al. (1976) found that the orchard (same specifications as above, 4.5 m spacing between row centres) allowed 13% more of the incoming direct beam radiation to reach the understorey if orientated East - West compared to North - South orientated rows. However, the distribution of the radiation is also significantly different for any area of pasture between East - West and North - South orientated rows. The spacial distribution of insolation in the pasture of East - West orientated rows is highly uneven (see discussion on shelterbelt edges 4.1.2) and this unevenness is reduced by a vertical redistribution of the canopy volume. As the sun track becomes lower in the sky hemisphere, East - West orientated rows enable less sunlight to get through to the ground compared to North - South rows.

In certain climates, the daily distribution of sunlight is very uneven. In Nepal for instance, during the monsoon in the mountainous areas, the sun often shines for a few hours in the morning before cloud obstructs any direct sun beam incidence for the rest of the day; under such conditions, East - West orientated rows would enable most insolation to reach the underlying pasture, whereas North - South rows may not allow any insolation through if the trees are tall and the rows close to each other. Allen (1974) found with his model of light penetration into wide row grain Sorghum grown in Colorado at latitude 40° N that on August 17th, North - South rows allowed 18% less direct beam radiation to the ground than East - West rows, North west - South east and North east to South west 14% less and random plant distribution 46% less. North west - South east rows allow greatest penetration in the morning hours and least between about 1.30 pm and 3 pm which may be important to inter row
production when the water status of the plant deteriorates during the day and when the metabolic reserves are lowest from photosynthesis of the previous day.

A characteristic of canopies which few light penetration models have so far taken into account is that of gaps in the canopy of individual trees and the direct beam radiation incident on the understorey through these gaps. The size of the gaps in relation to the angular size of the sun is of great importance and is determined by the height and depth of the crown, leaf size, leaf shape, leaf orientation and distribution within the canopy.

Gaps which are large compared to the sun's disc as seen from ground level enable the full intensity of the sun's radiation to create a sharp edged sunfleck on the ground. Such sunflecks enable high light intensity to reach the pasture at other times than that determined by the gaps between the trees. Their size and their movement in the canopy which is determined by wind speed and leaf, twig, and branch flexibility determine the time over which a specific spot in the understorey is thus illuminated. The smaller the gaps in relation to the sun's disc (an increasing occurrence as the distance between the canopy and the underlying pasture increases) the larger the area subjected to low direct sun beam intensity of unaltered spectral composition (penumbral effect). The more such small gaps there are, the more the low intensity sunflecks overlap and therefore the more even this low intensity radiation is likely to be. *Eucalyptus regnans* forest for instance, where clean boles may rise to 30 m in height and the leaves are small are likely to impose little spacial variation in light intensity on their understorey. Norman et al. (1971) have found that sizeable penumbral effects occur with canopies only 2 m in height.
The significance of taking penumbral effects into account is illustrated by Norman et al. (1971) with the tobacco plant which reaches a saturation value for photosynthesis of 20 mg CO₂ dm⁻² hr⁻¹ at ½ full sunlight. Using these characteristics to compute tobacco responses under a canopy with an average of 17% light transmission, markedly different production rates were found when the same average intensity was assumed to be: i) spread uniformly as an average transmission that gave an assimilation of 13.5 mg dm⁻² hr⁻¹; ii) reallocated as 4.6% diffuse background plus 12.4% of the area in geometric sunflecks (with the full beam intensity added to these sunflecks), which gave 6.0 mg dm⁻² hr⁻¹; and iii) the same as ii) except that the sunfleck penumbra were taken into account which gave 9.1 mg dm⁻² hr⁻¹. Using the actual local light intensity distributions which they had measured, gave 9.6 mg dm⁻² hr⁻¹.

The quality of light incident on the understorey and particularly the timing of the incidence of radiation of different qualities may vary significantly with differences in canopy structure. The relative enrichment of near infra red radiation to PAR (and 730 nm: 660 nm) increases with cumulative LAI, with low sun elevation angles and with clear skies (low diffuse radiation) (Allen et al. 1976). The ratio of 730 nm to 660 nm radiation is much greater in shade than in sunflecks; Allen (et al., 1976) measured ratios of 7.75 in a shady spot at the floor of a maize crop in August at 1200 hours (a clear day) while in a sunfleck the ratio was 1.05. This enrichment would be less pronounced under canopies which allow an evenly distributed low intensity direct radiation (overlapping penumbra) through to the understorey. In situations where higher light intensity sunflecks
are distributed within more shaded areas, wind, through its influence on spacial fluctuations in sunfleck and shade, should cause a dilution in the effects of far red enrichment (Allen et al. 1976).

4.1.5 Conclusion.

The measurement of light intensity in a way which is meaningful to the response of plants either in the understorey or adjacent to woodland is very difficult to achieve; however a thorough interpretation of production results obtained in an investigation to establish responses to environmental factors, must at least be aware of the usually unsatisfactory description of the light regime, both qualitatively and quantitatively - as some of the above examples have shown.

Any attempt at predicting the contribution of the light factor to understorey pasture response in a new environment from responses found elsewhere must at least take into account the differences in latitude, slope angle, exposition, tree row orientation, and the differences in the monthly and daily distribution of weather patterns. It must also be ascertained how representative of the growing period (including time of day) the measurements are at the location from which predictions are to be based.

4.2 Wind.

Trees and shrubs create an obstruction to airflow. The pattern of redistribution by trees of the moving airmass, and therefore the windspeeds (relative to that of open ground) vary at any point in the zone of influence of trees with the height...
of the barrier, with the vertical distribution of canopy sections of different permeability, and with the length of the barrier and its orientation in relation to the wind direction.

4.2.1 The effects of blocks of woodland on wind regimes.

It is generally agreed that for any one location, the distance windward and leeward from a windbreak over which wind speeds are reduced is proportional to the height of the trees. The degree of permeability of the block of wood, and the vertical distribution of canopy of varying permeability influence the degree and extent of shelter both leeward and windward.

Fig. 4.11 shows the generally accepted pattern and extent of wind abatement by belts of different permeabilities. A dense windbreak creates a turbulence of air which soon returns to the ground although a greater degree of shelter is provided immediately to the lee. A permeable belt enables the air stream of filtered reduced speed to "carry" the faster, vertically displaced airstream further away from the belt. A high permeability in the lower part of a belt increases the windspeeds both below the screen and in the lee and windward sides of the barrier; for short distances, the wind velocity can be increased to 115% of that found in the open ground though beyond a certain distance the wind speed will be lower than that in the open. At the edges of strips of woodland and in gaps through the strips, wind speeds can reach 110 to 120% of those in the open (Caborn 1957).

The width of a woodland influences wind abatement through reduced permeability with increasing width and therefore a block of woodland often reduces wind speeds in the same way as a dense shelterbelt (Fig. 4.12), although the downward turbulence leeward
Fig. 4.11. The influence of windscreens on the velocity of the wind, measured at a height of 1.4 meters over the surface.

--- Open

--- Medium dense Screens.

--- Dense

--- Very dense (From Van der Lynde 1962).
Fig. 4.12. Relative wind velocities in the vicinity of a large forest complex. (From Caborn 1957).
of a wide block of woodland is not likely to occur as much as to the lee of a dense narrow belt. Van der Lynde (1962) gave examples of both investigations which show increasingly large sheltered areas leeward of woodlands of increasing width, and of investigations which show the reverse. However there are difficulties in attributing the observed effects to the correct cause(s) since the structure and permeability of belts which are compared may vary, and since the influence of topographical features in the vicinity of belts which are compared also alter the turbulence of the wind.

The length of the barrier also determines the extent of leeward areas which experience different windspeeds (Fig. 4.13). It has been generally found (Caborn 1957) that a length 12 times the height of the barrier is required to obtain the maximum shelter effect in the centre of the sheltered area when wind is at right angles to the belt; however with winds varying in direction through $45^\circ$ either way of $90^\circ$ to the barrier, the length would have to increase to 24 times the height in order to utilise the full potential of distance protection.

The type and velocity of wind influence the relative shelter effect of a shelterbelt. The speed of the wind alters the permeability of the belt; permeability is reduced in Norway spruce belts with increasing wind because of the altered distribution of branches (Caborn 1957); this is also found with some Casuarina spp. and Casuarina glauca in particular; the reverse has been found with some Eucalypts where permeability increases with rises in wind speeds (Charfi 1975). The turbulence of the wind (which may vary with different wind speeds) alters the efficiency of a woodland in reducing speed - generally the more turbulence, the less the
Fig. 4.13. Zone of wind velocity abatement near a windbreak of moderate penetrability. (From Gloyne 1954).
efficiency. However, tree species which have flexible stems and branches, and fluttering leaves break up wind eddies more efficiently than more rigid species, and cause an increased energy dissipation (Radke et al. 1976).

For maximum efficiency, i.e. "to shelter effectively the greatest area" the optimum permeability is between 30 and 50% (Caborn 1957), though Read (1964) in the Great Plains of Nebraska and North Dakota reported the greatest corn yields leeward of windbreaks having a permeability of 20%. Van der Lynde (1962) and Caborn (1976) commented on the relative efficiency of shelterbelts in regions with different wind climates; the turbulence of wind generally increases with a more accidented topography and therefore the zone of shelter is relatively narrow compared to leeward zones of shelterbelts in wide open areas.

Windspeeds inside woodland are reduced and the distance from the windward edge at which the minimum wind speed occurs varies with the structure of the woodland (e.g. species composition, extent of brashing) and with the wind speed prevalent in the open. Fig. 4.12 gives the results found by Nageli (1953) in Norway spruce forest (average height 28 m). In Scotland a woodland (Scots pine and larch mixture) used for wintering cattle reduced wind speeds (in December) to an average of 35% of their maximum (in this case 9.5 m sec\(^{-1}\)) at 50 meters inside the plantation (though the wind speed reduction/distance inside woodland curve had not yet levelled out) (Cumming 1980).

4.2.2 Intimate mixtures and wind regimes.

There have been few studies on the wind regimes in areas with scattered trees. Nevertheless it is clear that windspeeds are reduced. When trees have a clear bole to a reasonable height,
it is quite likely that wind speeds may be greater than in the open for a short distance in the lower trunk zone, but soon wind speeds decrease to below those of open country (Hadfield 1975). Nageli (1961) investigated the wind regime along transects going through pastures with scattered Norway spruce trees in the Jura mountains; the height of the trees varied and their crown came close to the ground. At c. 120 stems ha\(^{-1}\) the wind speed was below 20% of that in the open; at about 35 stems ha\(^{-1}\) the wind speeds were reduced by c. 40% and at 10 - 15 stems ha\(^{-1}\) by less than 20%. Farnsworth et al. (1976) found in a *Pinus radiata* stand spaced at 3 m x 3 m, that winds were reduced as the trees aged as shown in table 4.1.

Table 4.1 Average wind speed at different heights within *Pinus radiata* stands of different ages (adapted from Farnsworth et al., 1976).

<table>
<thead>
<tr>
<th>Recording height</th>
<th>Control site km/h</th>
<th>Wind speed, % of control site.</th>
<th>Age of trees (years since planted)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 m</td>
<td>23.8</td>
<td>88</td>
<td>2</td>
</tr>
<tr>
<td>1 m</td>
<td>19.7</td>
<td>72</td>
<td>3</td>
</tr>
<tr>
<td>10 cm</td>
<td>13.4</td>
<td>60</td>
<td>4</td>
</tr>
</tbody>
</table>

4.2.3 Conclusion.

Although we have a reasonable general understanding of the influence of trees on wind patterns, the prediction of the aerodynamic characteristics of forest openings, and by extension areas with scattered trees, is likely to be difficult for any particular site because of the variability of the structure of the forest and of tree canopies and because of the possible variability in topography.
Further, conventional measurements of wind speeds often only average out a range of widely varying horizontal wind speeds; turbulence created by up and down air movements are difficult to measure, yet their influence on plants are likely to be as important as horizontal air movements. The difficulties in assessing wind patterns in the vicinity of windbreaks makes the prediction of their effect on the productivity of organisms even more difficult.

4.3 Precipitation and moisture.

Trees influence the amount of precipitation reaching the ground and its spacial distribution. They also influence the relative humidity of the atmosphere and soil moisture regimes (competition for soil moisture by roots between trees and pasture species is discussed in chapter 5).

4.3.1 Influence of trees on the incidence of precipitation.

Atmospheric precipitation.

Blocks of trees are unlikely to have an influence on the total amount of annual atmospheric precipitation over a large area (Lee 1980). Nevertheless they can significantly alter both the total amounts of precipitation reaching the ground and also its spacial distribution. Fig. 4.14 shows that the relative amount of atmospheric precipitation which is intercepted (i.e. which does not reach the ground) by tree and shrub canopies (and branch, stem) is related to the magnitude of the rain event. To a certain extent wind speeds also influence the degree of interception through their influence on evaporation rates (and therefore the interception storage capacity).

The impact of interception is much greater in climates with frequent small rain events and high winds (such as in the British uplands), while tree canopies have a negligible impact in areas
Fig. 4.14. The relations between the rainfall interception efficiency of tropical and temperate forests and the amount of rain precipitated by a storm. (From Oke 1978).
with infrequent large rain events such as tropical or monsoonal rainstorms. The range of values (probably based mainly from measurements in the temperate zones of the globe) for precipitation interception is 10 - 25% for deciduous trees and for conifers 15 - 40% (Oke 1978). Different species can have significantly different interception capabilities due to leaf shape, leaf surface and leaf angle characteristics. Older and taller trees seem to intercept more precipitation because of a greater LAI and of the greater height associating the canopy with higher wind speeds. Kittredge (1962) provided evidence from a number of investigations which indicated that percentage interception increases at an accelerating rate with an increase in crown closure (and basal area) although increasing wind speeds are likely to alter this relationship at least with narrow shelterbelts (see below).

The spacial distribution of through flow (precipitation reaching the ground) varies greatly between species. Lee (1980) provided figures for the average values of stemflow, as a percentage of precipitation, which show for example beech with a stemflow of 11%, oaks with 2%, Douglas fir and Lodgepole pine with less than 1%, though the proportion of stemflow varies greatly in deciduous trees between the leafy and deciduous phases. Pressland (1976b) reported on investigations in different parts of semi-arid Australia where the stemflow of mulga (Acacia aneura) trees constituted 18% to 40% of total rainfall incident over the tree canopy (for extended periods); while Pressland (1976b) in his area found that overall the proportion of precipitation concentrated in stemflow was lower than the other figures for Australia, he noted that it varied considerably between trees of different sizes and according to the size of the rain events.
Geiger (1965) gave figures for the spacial distribution of canopy through flow for different canopy types: in summer, a weeping type can have the greatest part of the understorey receiving less than 70% of the precipitation in the open, while the drip zone under the canopy periphery receives over 130% of that in the open.

The concentration of rainfall by different canopies into a through fall of large drop sizes can in some situations be of significance to erosion and soil moisture levels through a possible greater compaction and reduced soil infiltration capacity. *Alnus nepalensis* is said to have such a characteristic in the Himalayas (Kessler 1981). Geiger (1965) quoted an example where in the open no raindrops had a diameter greater than 2.5 mm, while about 25% (by weight) of the throughfall under oak had drop sizes greater than 3 mm.

The spacial distribution of incident precipitation both within and beyond the canopy zone of trees either as individuals or in blocks is also influenced by wind (Section 4.2) (Oke 1978). The distribution of rain in relation to the wind barrier varies with differences in air movements and the mass and aerodynamic properties of the raindrops. Blowing rain creates a rain rich zone to the windward side of the barrier, the width of which depends on the angle of inclination of the falling drops.

Dancette et al. (1969) found (near Bambeau, Senegal) that the throughfall under an *Acacia albida* canopy (averaged from different positions under the canopy) could be 22% lower (-1.9 mm) than precipitation in the open with fine rain events, while with driving heavy rain, it could be 29% greater (+9.5 mm). For a total of 325.5 mm of rain studied (8 heavy and 6 fine rainstorms - about half of the yearly precipitation) there was an overall increase of 28.7 mm under the tree (an 8.9% increase) compared to the outside
zone. However even with fine rain events, the distribution of throughfall under the canopy varied considerably: with one rain event when the average reduction in rainfall under the canopy was 4% compared to outside, the average for six rain gauges on the lee side of the canopy gave a reduction of 29% while the 6 gauges on the windward side gave an increase of 15% with resultant significant influences on the understorey vegetation.

Measurements of rainfall over 2 years in a clearing c. 25 m wide within beech and oak forest 25 m tall near Prague showed that due to the prevailing westerly winds associated with rain events, the eastern edge of the clearing received more than 100% of the precipitation found in the open, the western end received c. 70%, over $\frac{1}{2}$ of the clearing received between 70 and 90% while a small island in the middle received 95 - 100% of the precipitation (Geiger 1965). Over a 4 month period in Germany, rainfall readings were taken in the wind protected zone of a 40 m tall poplar shelterbelt; the percentage precipitation compared to that in the open was 7% at 4 m from the belt, 30% at 14 m and 70% at 24 m (Kittredge 1962). The rainshadow is therefore not likely to be significant beyond 1 or 2 H but will vary significantly according to the coincidence of the rain patterns with direction and speeds of wind in relation to the tree barrier.

Oke (1978) asserted that light rain or snow suspended in the air tends to be preferentially deposited in the zone of least wind speed around obstacles such as shrubs or trees. However since detailed aerodynamic characteristics in the vicinity of belts and particularly scattered trees (section 4.2) are difficult to predict, it is difficult to assess the likely detailed distribution of precipitation either in the vicinity of such barriers, or within blocks of scattered trees. A good example of the variation in
incident precipitation amongst scattered trees is provided by the Farnsworth et al. (1976) example with Pinus radiata mentioned above (section 4.2; table 4.1). Although the general pattern was one of reduced precipitation reaching the ground within stands compared to open ground, in 2 months out of 3, the average precipitation was higher for the 7 rain gauges per plot in the 5 year old than amongst the 2 year old trees; further in one month the precipitation reaching the ground was 5% higher in 5 year old trees and 35% higher in 3 year old trees than in the open.

It seems, nevertheless, that beyond the rain shadow area, any increase in precipitation can only be a function of the reduced precipitation over the barrier. This can occur with increasingly high winds and with smaller sized rain drops because the obstruction forces air up and the wind speed as well as the angle of inclination of the falling rain drops increase. The raindrops are therefore spread over a greater area and consequently the precipitation is reduced over the barrier (Lee 1980). To the lee, beyond the rain shadow, precipitation increases as the wind speed and the angle of inclination of precipitation drops. For rain however there are no records of increases of much more than 5% over volumes found in the open (Kittredge 1962, Van der Lynde 1962, Lee 1980).

When precipitation falls in the form of snow, it is possible that both the reduced wind speeds and the downward turbulence increase the amount reaching the ground to a greater extent than for rain. An investigation in the Russian steppes indicated that 29.5% less snow fell in the open than in the lee of a belt (Van der Lynde 1962).
One has to be careful however, in the interpretation of such measurements since rain/snow gauges can significantly underestimate actual precipitation in windy conditions depending on their vertical positioning and aerodynamic structure.

In addition to the effect on precipitation distribution, trees in blocks, strips or as scattered individuals are very important in reducing the drifting of snow. The most uniform distribution of snow is obtained with narrow belts which are more penetrable to wind near ground level. Reports from America of such belts enabling a snow mantle 30 - 60 cm deep to settle over 200 - 600 m to the lee of belts and thereby increasing soil moisture by an equivalent of 25 cm are recorded by Caborn (1957) (but only half that depth being deposited in the first 25 m). On the other hand narrow dense barriers trap the snow within a short distance on the lee side. Wider belts characterized with the appropriate permeability are able to trap most of the snow either close to or within their confines.

Fog drip and rime.

The branches and leaves of trees can concentrate small water droplets from cloud or fog. The amounts so derived by any particular area depend on many factors such as the frequency of the clouds or fog, the wind speeds and direction, the exposure, the density and height of the vegetation. The significance of this phenomenon as a contribution to overall precipitation depends not only on its quantities relative to total precipitation but also to its seasonal occurrence in relation to other forms of precipitation. It's spacial distribution on the ground again depends on the canopy structure.

On the Eastern slopes of the Washington Cascades, rime (frozen accumulation of supercooled water droplets) contributes
c. 100 mm of additional precipitation over the winter season. In some parts of California point measurements of fog drip have shown an additional net precipitation of more than 750 mm annually (Satterlund 1972). In *Eucalyptus regnans* stands near Melbourne in winter months, fog drip provided 222 mm (equivalent to 44% of the precipitation in the open) (Kittredge 1962).

Fog drip caused by trees and shrubs can be of particular significance in coastal areas of arid regions; gains have been reported in Israel, Chile and Hawai (Ward 1975); in the Canary islands, there is evidence of precipitation under trees being 3 times that in the open - the difference being due to fog drip (Kittredge 1962); while in the desert coastlands of Peru, low forest can grow at certain altitudes where fog oases occur (Longman et al. 1974). Reports of *Zyziphus* vegetation under *Prosopis cineraria* in parts of Oman being much greener than in open areas are said to be due to the *Prosopis* trees getting the bulk of their moisture from heavy ocean fogs (Felker 1981).

**Dew**

Since trees can reduce wind speeds, increase air humidity and influence radiation balances, they can have an influence on the incidence of dew on an area of ground in two ways:

i) the dew may form on and be released by the trees;

ii) the trees may influence dew formation on adjacent open ground.

There is some controversy concerning the quantities of dew which can be formed and concerning its relative importance to vegetation.

Monteith (1973) calculated that the maximum possible nightly quantities of dew fall are in the range 0.2 to 0.4 mm depending on wind speeds and relative surface cooling, but when the air is
saturated. He also suggested that such quantities are an order of magnitude smaller than potential evapotranspiration rates and therefore dew can rarely make a significant contribution to the water balance of vegetation even in arid climates. However others disagree: Rosenberg (1974) suggested that under favourable conditions, dew fall may be up to 2 to 3 times those suggested by Monteith.

The maximum amount of dew forms with low (but not non-existent) windspeeds, high surface cooling (long wave radiation loss) and high air humidity. Dew fall has been found to be 200% greater in areas sheltered against the wind compared to exposed ground; the heaviest dew fall being in one situation over a distance of 2–3H on the lee of a windbreak (Caborn 1957). With trees scattered over a pasture, there would be an optimum diameter for gaps between trees for dew formation at ground level determined in part by the reduced sky view factor (and therefore surface cooling). Any dew settling also evaporates later from a sheltered site due to the lower wind speeds (unless the sheltered area lies to the east of a belt when higher early radiation loads would increase the evaporation potential).

It would seem that with an increased volume of canopy per unit area of ground in contact with moving humid atmosphere and with a capability for radiative cooling, there is a potential for higher dew accumulation. Widely spaced trees may provide a system where maximum amounts of dew are formed. Kitteredge (1962) reported that in Europe and N. America the deposition of dew in forest can amount to one mm in a single night whereas in the open 0.1 to 0.4 mm is more likely. However he suggested that in the tropics ten times as much dew can be formed as in northern latitudes: a report from the Panama Canal zone mentions the steady drip from
dew at night. The type of crown and foliage has an influence on the incidence of dew deposition, Longman et al. (1974) mentioning that in tropical Africa large digitate leaves condense abundant dew.

The type of crown and leaf size, shape and inclination have much influence on the proportion of dew and fog drip which remains in the canopy and is reevaporated; Longman et al. (1974) suggested that when the leaves do not concentrate the dew into large drops, or when the leaves or leaflets are small, the water does not reach the ground. The canopy characteristics affect the redistribution of water to the ground in the same way as precipitation.

4.3.2 Influence of trees on atmospheric humidity.

The impact of trees and shrubs on the atmospheric moisture relations of neighbouring pasture plants are rather complex. One is interested in assessing the effect of the atmosphere on the evaporation from soil and plant surfaces, and on the transpiration from plants; hence the relevant atmospheric characteristic is the vapour saturation deficit (the difference between the actual and the saturation pressure) at the stomatal opening - atmosphere interface. The magnitude of the saturation deficit at that point is determined by the specific humidity (ratio of mass of water vapour to mass of moist air in the sample - kg kg$^{-1}$), the temperature of the air sample, and the barometric pressure; however a fourth factor, wind, disturbs the moisture gradient which becomes established at the stomata - atmosphere interface and therefore in effect increases the saturation deficit at that
point. Unfortunately many assessments of atmospheric humidity are in terms of relative humidity (the ratio of vapour pressure to saturation vapour pressure); as the saturation vapour pressure rises at an accelerating rate with increasing temperature, relative humidity is not a good measure of the "drying power" of the atmosphere where air samples vary in temperature. Hence since daily temperature variation can be markedly different between stands of different density (section 4.4), so the daily saturation deficit will vary. However independently of the temperature effect, vapour pressure differences occur between open ground, sheltered ground, and the lower storey of stands of scattered trees.

Generally, near ground level in woodlands, the water vapour pressure is greater than at any other height in the canopy and also during the day, greater than at ground level outside the stand (Geiger 1965 in temperate woodlands, Longman et al. 1974 in tropical forest in S.W. Ghana). The water vapour pressure near ground level does fluctuate during the daily cycle with a minimum late in the night due to the reduced transpiration caused by lower temperature, and a low in early afternoon due to the water vapour being transported away rapidly by increased convective mixing. The maxima are in early to late morning and in the early evening (Geiger 1965). However Kittredge (1962) described a situation in the Western U.S. where the vapour pressure over the soil in a Pinus radiata stand was lower than in the open; here the winds from the Pacific Ocean about 10 km away brought in moisture and the Pinus radiata crowns absorbed the atmospheric moisture while the moisture laden air was not affected before reaching the open ground.

The difference between the vapour pressure in open ground and underneath stands varies with the season. Kittredge (1962) quoted
an example from an oak forest in Tennessee where in December, the vapour pressure was higher in the open than under the stand (by 0.4 mm Hg or 10%), while in August the difference was 1.1 mm Hg or 7%. The largest difference was in the months when the trees were in leaf and transpiration was at its maximum; however in all months, including December, the vapour pressure deficit was greater in the open than in the forest, chiefly as a reflection of temperature differences.

In Missouri the difference in vapour pressure deficit (at 35 cm above ground) between a stand of hickory (Carya sp. - 400 stems ha⁻¹) and in the open (blue grass pasture) was found to vary with time of day. During the night, the open field had a 14.3% smaller vapour pressure deficit (mainly due to higher temperatures under the tree canopy) while during the afternoon, it was greater by 35.9% (3.07 mm Hg). However taking into account daily wind speed variations between the open and woodland sites, the evaporation potential (cc hr⁻¹) was 38.3% less in the open at night and 59.9% greater in the afternoons (Kucera 1954).

Kittredge (1962) also reported on a study from Idaho which determined that with a reduction in stand density by half (old forest of Pinus monticola, Tsuga heterophylla and Thuja plicata) the absolute humidity at 4.30 pm was reduced to 6.62 g/m³ from 7.69 g/m³ in the closed stand; the open ground absolute humidity was 6.47 g/m³. However it must be remembered that measurements of differences in vapour pressure deficit taken only once in the day may mask the amplitude of the differences at other times since the timing of the fluctuations.
in vapour pressure deficits are usually not similar in open ground and inside stands.

Farnsworth et al. (1976) in their microclimatic measurements of widely spaced *Pinus radiata* in New Zealand unfortunately measured relative humidity.

In the vicinity of woodlands or shelterbelts, the humidity conditions are also complex. The reduced wind speeds result in reduced moisture transport away from the moisture source, and therefore in higher absolute humidities by day and by night (Oke 1978). In Nebraska, air vapour pressure in August and September in sheltered plots was greater than in open plots by 1 to 6.7 mbars (Rosenberg 1974). Caborn (1957), Van der Lynde (1962) and Marshall (1967) concluded that saturation deficits in sheltered areas can be higher during the day and lower at night than in open areas. This is because the temperature may be greater than in the open to the extent that it negates the impact of the higher vapour pressure. In the Russian steppes, the temperature patterns during daylight hours provide for a reduced deficit during late afternoon (when the weather is dry and hot) and a higher deficit in the morning when shelterbelts enhance the warming up of the atmosphere (Van der Lynde 1962). However Rosenberg (1976) referring to the effect of shelterbelts on the Great Plains (U.S.), suggested that the effect of higher temperatures in sheltered ground on the drying power of air is generally negated by the higher vapour pressures.

When the blocks of woodland are large enough, the movement of air from the woodland to the surrounding pasture may reduce the vapour pressure deficit by both lowering the air temperature and also because of its inherently higher absolute humidity. This
Can happen with any wind originating from outside the area; however Caborn (1957) suggested that such a cool, humid airflow can originate from the forest itself and usually occurs towards the evening.

The extent of the open area which can be subjected to higher humidities must however be small although a large area of woodland should obviously increase the areas experiencing a moister atmosphere.

Caborn (1957) rightly concluded that "no general quantitative values can be assumed for the increased degree of humidity in the vicinity of shelterbelts (and larger blocks of woodland) because of the extremely varied conditions under which measurements have been recorded"; i.e. the atmospheric humidity is influenced by wind, air temperature, transpiration and evaporation from the vegetation, the type and extent of adjoining woodland, and by the moisture content of the surface soil. It also depends on the time of day, the season and the weather conditions (prevailing winds etc).

4.3.3 Influence of the aerial parts of trees on soil moisture.

Soil moisture relationships in areas protected by trees are a complex integration of the climatic factors which may have been altered by the trees: precipitation (rain, snow), dew, fog, evaporation, transpiration, atmospheric humidity, air and soil temperature, solar radiation, differential soil freezing and therefore infiltration of snow melt.

Soils to the lee of shelterbelts or blocks of woodland usually have a higher soil moisture than in open ground, when there is a regular pattern of wind direction - at least at critical times of year. However close to the woodland in areas where
precipitation is in the form of rain rather than snow, the soil may be drier than in open ground due to reduced precipitation intensity (see section 4.2). When the increased soil moisture is due to the control of distribution of precipitation — particularly snow, the structure of the woodblock, through its influence on the wind regime, determines the location of deposition of snow layers of different thicknesses. An example was given above (4.3.1) on the increased water availability through snow trapping on an extensive flat area in America. Rieben (1957) described the benefits which trees can be to soil moisture through influences on snow distribution in undulating country in the Jura Mountains. Without trees, snow drifts and settles in depressions, where because of its thickness it lasts longer into early summer and therefore reduces grass productivity. In the depressions the soil moisture regime is favourable even without snow accumulation. On the other hand large areas of pasture are prematurely freed of their protective snow cover; not only is there therefore less snow in the areas for replenishing soil moisture, but the soil freezes to a greater depth: this can damage plants in cold years in a way which is detrimental to subsequent growth and also reduce the possibility of infiltration at snow melt.

However considerably higher soil moisture in soils to the lee of shelterbelts can also be due to reduced evaporation. Caborn (1957) referred to studies in vineyard areas of Russia where the soil moisture was 25 — 30% higher (to a depth of 1 m), to a distance of 10 — 12 h from shelterbelts compared to vineyards in the open; although close to the shelterbelt, in the rainshadow, the moisture was 20% lower than in the open. In Germany the soil moisture content in an area of bare ground was 6.5% where exposed
to wind and 12.1% between shelterbelts during April; under a crop
between May and September, the moisture content was 6.4% and 10.5%
in exposed and sheltered sites respectively. Van der Lynde (1962) reported that the beneficial effect of shelterbelts on soil moisture is much greater during dry periods. Lynch et al. (1980) near Armidale (Australia) found that there was a significantly (P < 0.001) lower water loss from the top 30 cm of soil of a sheltered compared to an open pasture. When the windbreaks (artificial, 50% porosity, 1 m high) were placed 30 m apart, 12.3 mm of moisture was saved over 29 days. In such areas where several drying periods occur and water is the major limiting factor during the growing season, such water conservation measures should result (and did) in increased forage availability both prior and subsequent to the major rainy period. Nevertheless Sturrock (1975) suggested (based on evidence) that increased evaporation from soil surfaces may occur in the lee of dense shelterbelts compared to open ground because of the increased turbulence leading to greater vapour transfer.

The often mentioned beneficial effect of forest which occurs up-
-hill of pastures in maintaining a regular flow of water to the soils of the pastures, below must be mentioned. The phenomenon undeniably does occur and can be of particular value in enabling pastures below forest not to suffer as much in drought years - e.g. in the Jura (Rieben 1957). However as Satterlund (1972) concluded, such a phenomenon is due to the infiltration rate in forest land being greater than the increased evapotranspiration from the forest. This may not be primarily due to inherent differences in infiltration capacity between the forest floor and pasture, but to the soil compaction usually associated with pasture use.
The soil moisture regime of pastures which are in intimate mixture with trees are complicated to a greater extent by the competition for moisture than in a situation where the pasture is separate but adjoining to the trees (see section 5.1). Further the very variable pattern of wind, radiation and precipitation regime within short distances should theoretically allow for marked variations in soil moisture concentrations over short distances. Since it is not easy to dissociate such environmental reasons for soil moisture variations from competition factors, variations which occur subsequent to soil moisture replenishment are discussed in section 5.1. However as far as precipitation distribution effects are concerned, it is the subsequent redistribution at ground level or within the soil, of the unevenly distributed precipitation, which would influence the spacial distribution of moisture in the soil; this would vary with different soil types.

Pressland (1976b) in his mulga stand in Queensland, found that during rainfall events of various sizes and intensities all the stemflow of mulga (see section 4.3.1) infiltrates within 50 cm of the bole of large trees and 30 cm of small trees (bole circumference > 40 cm and < 20 cm at 30 cm height respectively); this is because of the greatly improved infiltration capacity of soils close to the bole. On the basis of area of infiltration, the soil water increase close to the bole is up to 200% greater than water replenishment in the open depending on the size of the crown and the size of the rain event. The water is also stored much lower in the soil profile than in the open areas.

Anderson et al. (1979) in Western Australia (precipitation c. 900 mm year⁻¹ but during years of experimentation precipitation considerably lower than long-term average) found that soil moisture
in the top 10 cm of soil in 13 m high Pinus radiata was not obviously affected by tree density (varying from 143 - 261 stems ha\(^{-1}\)) during the wet spring (mid September to mid October - 12 soil samples from each tree density at each sampling date). Further the moisture content was significantly higher (P < 0.001) by c. 10% (difference between 23 and 33% soil moisture by weight) in pasture under the pines compared to an adjoining treeless pasture during this period.

Near Fort Victoria (Zimbabwe) Kennard et al. (1973) compared soil moisture recharge in pasture in open grassland sites, in adjacent sparsely wooded (open Savanna) sites, and in closed woodland (composed of many tree species). They found that the rate of water infiltration and the water holding capacity was much higher in soils under trees than in the open (6 sample per site).

The extent to which a better soil moisture condition can prevail in any situation in pasture land under scattered trees compared to open pasture independently of direct competition between trees and pasture plants, must depend on the several climatic factors mentioned in this chapter including particularly the size of the rain events and on the concurrent wind conditions - i.e. on the proportion of precipitation intercepted; where the rain events are small, frequent and interrupted by periods when evaporation from the canopy is high, the soil conditions under tree canopies could be much dryer than in open grassland.

4.4 Temperature.

Since short wave radiation is the chief source of heat of both air and surfaces, the factors mentioned in section 4.1 which affect the incidence of radiation are likely to influence air and
surface temperature regimes. Differences in moisture levels (4.3) influence the amplitude of temperature change for a given energy input since water has a high specific capacity, and through changes in latent heat exchange. Wind patterns (4.2) may alter temperature patterns by advection of air masses of different temperatures and through the alteration of air temperature gradients by air mixing leading to changes in the rate of sensible heat transfers to and from the atmosphere. Trees also influence the rate of loss of heat from underlying surfaces through their obstruction of long wave radiation to the clear sky.

If temperature comparisons are to be made between sheltered pastures or intimate tree pasture systems and open pasture, to explain part of the differences in animal and plant responses between the two environments, the temperature measurements must be made in such a way that: i) they are comparable; and ii) they are measuring the differences at locations in space and time which are of importance to the organisms concerned. For livestock air temperature and surface temperature readings have to be at the height of the main part of the animals at different times of day. For pasture plants, root zone soil temperatures are important, but the same species may root to a different depth depending on the extent of shelter, shade etc.; if pasture plant leaves grow at a rate dependent on the temperature of their apical meristems (true for grasses), the height at which air temperature has to be measured in grasses is close to the ground surface (Grace et al. 1979); while in dicotyledonous plants, it may be towards the top of the plant canopy which may vary in height between sites with different microclimates (other than temperature) if growth rates are different.
4.4.1 Temperatures adjacent to woodland.

Soil temperatures.

A large number of studies have looked at differences in soil temperature patterns between open ground and in the lee of shelter-belts or blocks of woodland with varying results. It is however very difficult to know what factors to attribute qualitative and magnitude differences to: the heat capacity and thermal conductivity of different soils varies considerably (see table 4.2); since the degree of wetness also influences the soil temperature, rain-shadow effects (drying) or snow accumulation (wetting) will have a warming and cooling effect respectively.

Table 4.2 Heat capacity ($J m^{-3} K^{-1} x 10^6$) and thermal conductivity ($W m^{-1} K^{-1}$) of different soils (from Oke 1978).

<table>
<thead>
<tr>
<th></th>
<th>Heat capacity</th>
<th>Thermal conductivity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Dry</td>
<td>Saturated</td>
</tr>
<tr>
<td>Sandy soil</td>
<td>1.28</td>
<td>2.96</td>
</tr>
<tr>
<td>(40% pore space)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Clay soil</td>
<td>1.42</td>
<td>3.10</td>
</tr>
<tr>
<td>(40% pore space)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peat soil</td>
<td>0.58</td>
<td>4.02</td>
</tr>
<tr>
<td>(80% pore space)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Marshall (1967) reported temperature increases of more than 2°C at midday at depths between 2 and 10 cm in the lee compared to an unsheltered site. On clear nights, because of airflow modification, sheltered sites are likely to have lower temperatures than in open ground (Marshall 1967, Skidmore 1976).
Read (1964) quoted examples from Russia where soil temperatures were 3°C warmer in the lee at 10 cm on cool windy mornings; an example in Nebraska showed at 50 cm depth 2°C less in spring and summer at \( \frac{1}{2} H \) and 0.5°C warmer at 2H compared to open ground, and 2 - 3°C less during the autumn and winter. However if a deeper snow cover occurs in the lee, warmer soils may occur in winter. Read (1964) concluded that generally spring and summer soil temperatures are higher than in the open while in winter and autumn temperatures are lower. Gloyne (1954) suggested that soil temperatures in the lee of shelterbelts, but away from radiation influences, are likely to show higher day maxima at 10 cm depth of 0.5 - 3°C relative to open ground, with larger differences near the surface. Cloudy and wet conditions are likely to reduce the temperature differences between soils in the open and in shelter.

Close to woodland the incident radiation can markedly vary according to the factors mentioned in section 4.1. Kittredge (1962) found in Minnesota that maximum soil temperatures in July on the northern edge of a woodland were 1.6°C, 4.8°C and 9.4°C lower at \( \frac{1}{2}, \frac{1}{2} \) and \( \frac{1}{4} \) the woodland height away from the stand (open ground maximum 31°C). Southern edges may experience markedly higher soil temperatures particularly with northerly winds.

However it would seem that without a detailed understanding of the processes involved, these data are of little value in predicting what temperature regimes may be expected in sheltered sites in different locations. A moister soil leads to greater conduction of heat to lower soil layers, to a reduced heating capacity, and through evaporation, to an increased heat loss. The amount of vegetation covering the soil, and its insulating capacities, which may vary between sheltered and unsheltered
sites due to other factors, would also alter the soil temperature regime.

The temperature of air and of biological surfaces.

Because of the difficulty of measuring surface temperatures, most of the data available are on air temperatures taken at the same height in the open and in the sheltered site. However it is only meaningful (in terms of plant response) to compare temperatures between sheltered and open sites at the same height above the ground if one can be sure that the slope of the temperature to height above ground gradient is the same for the two sites, a situation which is increasingly unlikely when the two sites experience different wind speeds and turbulence.

It seems that generally, under windy conditions and with clear skies, the daytime temperature of sheltered sites is higher than that of open sites, and the night time temperatures are lower. Caborn (1957) quoted numerous investigations which have shown that daytime maxima are higher by \(1 - 3.5^\circ C\) to a distance of c. 5 H, and \(1.2^\circ C\) higher from 5H to 10H at 1.20 m above the ground. During very hot days the temperature in the zone adjacent to a belt may be \(6 - 7^\circ\) higher than in the open. During the night, the minima may be lower than in the open by the same amount as the higher maxima. Similar trends have been reported under certain conditions by Geiger (1965), Marshall (1967), Van der Lynde (1962), Alcock et al. (1975) for upland Wales, Skidmore (1976) for the Great Plains in the U.S., Grace et al. (1979) for upland Scotland, and Charfi (1980) for subsahara Tunisia.

There are 4 main components of the shelterbelt pasture system which should be considered separately in terms of their impact on the temperature regimes of pastures.
The influence which the woodland has on the temperature of air masses moving from the woodland to the adjoining area;

The influence which the woodland has on the flux rate of sensible and latent heat loss or gain through alteration of the boundary layer;

The influence which the woodland has on radiation loss or gain;

The indirect woodland influences which are pasture mediated; i.e., rather than the temperature difference being the cause of the pasture response, it is the effect of the pasture response to other altered environmental factors.

(i) Little information seems to be available on the first point. It is clear however that the potential warming or cooling of the air mass relative to that which is achieved by open pasture can only be achieved to a significant extent by wide shelterbelts and larger blocks of woodland.

Geiger (1965), referring to temperate forest, suggested that the outer edge of a wood can be cooled during the daytime as cool air from the trunk area flows out into the open. The extent to which this can happen must depend partly on the permeability of the forest edge. At night, particularly in mountainous country, a downflow of cool air occurs from the radiating crown area. In winter, in temperate and northern areas, the temperature is higher inside the forest (even if deciduous) than outside (Kittredge 1962).
However the temperature influences which can be carried over a larger area than that of the immediate forest edge, are due to the temperature developed in the air mass above the forest (through canopy heating or cooling) and subsequently transported by wind. Pavari (1962), based on air temperature measurements from ground level to 1000 m above ground, suggested that the air mass temperature above forest can be constantly below that found above open ground up to 500 m when the forests are transpiring, with maximum differences at night. However he found above a xerophilous coppiced holm oak maquis in Italy that the temperature was higher than above open ground for the eight months of the year when transpiration is greatly reduced due to moisture deficits. The higher temperatures can amount to 3 or $4^\circ C$ differences and can be experienced to a height of 500 m. He suggested that a similar warming effect of the air mass occurs in other xerophilous regions and provides supporting evidence from Californian Chaparral.

The extent to which the forest-cooled or warmed air masses contribute to temperature differences between animal or plant environments adjacent to forest stands and in the open must depend on the degree to which they are able to influence the temperature gradients in the boundary layer. This is likely to depend on wind regimes, topography and on the distance of the site to the forest edge.

(ii) Section 4.2 discussed the influence of stands of trees of different sizes and structure on the wind speed and turbulence of adjoining open areas. As the depth of the boundary layer, and its temperature gradient influence the extent to which sensible and latent heat loss from surface areas can take place, different
types of woodland will have different degrees of influence on the temperature regime of surfaces at different distances from the woodland edge and at different heights above the ground. Generally, plant and animal surfaces will be warmer during the day, if the sun is shining, than in the open because of the reduced ability to lose sensible heat. Hadfield (1975) showed under controlled conditions that the leaves of *Camellia sinensis* (var. assamica) exposed to 63 k lux radiation had a temperature of 45°C with no wind, 33°C with a wind of 0.8 m sec⁻¹ (directed at the leaf straight from a fan), 30°C at 1.7 m sec⁻¹ and between 29°C and 30°C at 2.5 m sec⁻¹. However as Grace et al. (1979) and Rosenberg (1976) suggested, this is not always true since an increased capacity for transpiration in shelter may reduce plant surface temperature compared to those in open ground. From preliminary results in sub-saharan Tunisia, Charfi (1980) suggested that, during hot and dry weather, windbreaks made the situation worse for dryland farming but may improve the growth conditions for irrigated crops. Under overcast conditions, little difference in air temperatures occur (Van der Lynde 1962, Marshall 1967), although sheltered surfaces, may be warmer or cooler depending on their evaporation rates. With precipitation, reduced wind speeds in the lee of a woodland (and particularly in the rainshadow) reduce the evaporative cooling of the surfaces and therefore of the air close to the surfaces. The greater night-time cooling in the sheltered zones takes place only when radiative cooling is possible, i.e. with clear skies, and when there is a wind which prevents the temperature inversion from developing in the open; the wind being reduced to such an extent in shelter that a stable inversion may develop. Caborn (1957) and Van der Lynde (1962) reported that the lee experiences a higher temperature than in the open in the morning and early afternoon, and that when the radiation balance is negative, sheltered zones
experience colder temperatures than in the open.

While Skidmore (1976) noted that usually higher daytime, and lower nighttime air temperatures occur in sheltered zones, he quoted research which had also found cooler air temperatures in the lee; in the latter case, the leeward air temperatures were closely related to the eddy zone produced by the barrier, warmer air conditions over an area up to 5 - 10H where the warm eddy currents were rising; beyond 5 - 10H, the day temperature being lower than in the open due to a mean downward vertical flow of air. Skidmore (1976) also found that the air temperature over evaporating Sudan grass at 2H leeward was higher than at 6H windward by 0.9, 1.2 and 1.5°C for 60%, 40% and 0% porous barriers respectively. However this kind of temperature response would be likely to vary with different wind speeds. A non porous wind break for instance would be likely to create high air turbulence immediately to the lee which would reduce the air temperature differences.

(iii) The shortwave radiation effects of a woodland edge are not likely to be important beyond c. 2H except on north facing slopes. In the shade of the woodland, daytime temperature is lower than in the open. The radiative temperature of a cloudless sky is often 20°C lower than ambient air temperature, while tree canopies have seldom more than a few degrees of difference from air temperatures (Grace et al., 1979). Therefore there is likely to be a significant difference in surface temperature within short distances from a forest edge due to the differences in sky view factor. When a woodland edge remains shaded for a significant part of the day, surface temperatures (measured by a radiation thermometer) have been found in Holland to be
often 6 - 8°C and sometimes 10°C below ambient temperature due partly to long wave radiation loss and partly to the day evaporation of the dew from the surfaces (Stoutjesdijk 1974).

For the first part of the night however, long wave radiation input may occur from the woodland.

On the edge exposed to solar radiation, the energy input to pasture surfaces is higher than in the open due to reflection of the woodland edge (section 4.1).

(iv) There can be a whole range of reasons why the air and surface temperatures may be different in the lee than in the open which have to do with the shelter effects on other characteristics of the system. The plants may have a different energy balance: the area of leaves may be larger (Radke et al. 1975); the plants may be taller with a resulting shift of the boundary layer upwards (Radke et al. 1975, Sturrock 1975) making the design of temperature measurements of different sites difficult. Reduced moisture deficits experienced in the sheltered zone, through greater soil moisture concentrations, through greater rooting depth (Sturrock 1975) leading to greater transpiration should reduce the air temperature close to the surface compared to that in unsheltered sites. Hadfield (1975) found that for tea leaves (Camellia sinensis var. assamica - horizontal leaf variety) under high radiation load in the field, the cooling effect of transpiration was about 5°C when the air temperature was c. 30°C. The albedo of sheltered plants may be different (independently of altered light spectrum close to the forest edge - section 4.1), resulting in a changed energy gain.
4.4.2 Soil, air and surface temperatures in intimate mixtures.

While in general, pastures amongst scattered trees experience a temperature regime intermediate between sheltered pasture and the trunk zone of the forest, important divergences can occur depending on the exact structure of the system and the time of year and time of day. For instance Geiger (1965) noted that the temperature regimes within thin stands are markedly different from dense stands. A thin stand (tall pine and beech mixture in Germany in September) had a forest floor temperature at noon 1°C colder and at night 5°C colder than upper canopy temperatures, while in a dense stand (fir plantation near Munich in July), the ground temperature was 6°C colder at noon and 1°C colder at night.

It is again worth separating the causes of differences in temperature into the 4 contributory components outlined in section 4.4.1.

(i) The influence of scattered trees on the heating or cooling of the air mass at different heights above the ground and at different times of year, is likely to depend on the density of trees, on the yearly pattern of the albedo of the canopy, on the yearly and daily patterns of evaporation, on the vertical distribution of the canopy volume and the time pattern of radiation incidence on the different vertical levels of the canopy. Scattered trees, with a shallow high crown are likely to have no daytime temperature effect on the air mass in the understorey unless vigorous vertical mixing of air layer brings heated air from the upper canopy down to the lower layers as noticed by Geiger (1965). At night however, the air cooled by the crown area may sink to the understorey level, the average
temperature being therefore lower than in the open. On the other hand, narrow deep canopies and particularly low dense canopies could enable higher day temperatures of the air mass to be established, particularly when evaporation by the canopy is restricted. Pavari (1962) attributed the higher average monthly temperature of the air mass within chaparral (in California) and holm oak coppice maquis (in Italy) by several degrees for several months of the year compared to air in open ground to such canopy and evaporation characteristics: from March to September, the Italian maquis forest showed and average monthly air temperature of 10°C or more greater than open land. The higher average temperatures are likely to be due to significantly higher day time temperatures compared to open ground since night temperatures may be lower than in open ground. The Californian Chaparral showed summer peak temperatures exceeding those in the open by more than 4°C, the average July maxima being c. 3°C higher than in the open.

(ii) Although the wind speeds and turbulence in open stands are reduced, the vertical distribution of different air current patterns are likely to vary with the vertical distribution of canopy volume (section 4.2), thereby influencing the boundary layer and the latent and sensible heat fluxes from the pasture. On the Kenyan Coast, Goldson (1973) found consistently higher day-time temperature maxima in pastures with scattered cashew trees compared to pastures without trees; he attributed this higher temperature to an overall reduction in wind speed of 67% over the 2 year study.

(iii) Although the average shortwave input to the pasture is greatly reduced by scattered trees (section 4.1), what is important to organisms is the daily distribution of periods of different radiation mediated temperatures. Closed but light canopies enable an even daily distribution of shortwave radiation input and therefore less fluctuations in surface temperature due to radiation fluctuations. On the other hand, open but dense canopies would lead pasture plant surfaces to being cooler than
air temperature for several hours in the day when not exposed to radiation, and several degrees above the ambient temperature for the hours of the day when exposed to full radiation (10°C higher in the case of Camellia sinensis var. assimica leaves during the harvesting season, Hadfield 1975).

The pasture surface may cool less than in the open due to reduced capacity for long wave radiation loss.

(iv) Similar factors as those mentioned in 4.4.1 are involved. In climates where high canopy interception levels take place, reduced evapotranspiration potential by pasture species could lead to periods when the temperature would be higher than in open country. If the transpiration is reduced due to the higher shoot to root ratio (section 2.1) or if the area of leaves is larger (section 2.1) then surface temperatures could be higher than in the open, at least when the plants are exposed to solar radiation.

It is the integration of the four above components acting together which determine the yearly and daily timing of temperature regimes of different amplitudes at various horizontal and vertical sites in the intimate tree pasture system. Farnsworth et al. (1976) found that for their Pinus radiata farm forest plantation (details in section 4.2.2) the annual air temperature range (average of measurements at 1 m and 10 cm ) increased by both higher maxima and lower minima between the open site and planted sites and as the trees aged up to 5 years of age (the annual range was 5°C higher in 5 year old pines than in open pasture). However the air temperature range in 6 year old pines was lower than in all other sites (by c. 8.5°C between itself and the plot with 4 year old trees). This was probably related to the
increasingly raised tree canopy with age, to the associated reduced short wave radiation input to the underlying pasture, and to the increasing wind velocities developing under the canopy zone on this site with older trees.

Soil temperature differences between intimate tree pasture systems and open ground are influenced by the same factors as those mentioned in section 4.4.1. Generally the average and the range of soil temperatures in summer time (in temperate and northern latitudes) is lower in scattered woodland than in the open (Farnsworth et al. 1976, Kittredge 1962) - and for the whole year in subtropical and tropical climates (Kennard et al. 1973). In winter at high latitudes, the average soil temperature may be higher than in the open (Kittredge 1962). It could however be, that in situations where the soil is considerably drier amongst scattered trees than in the open (section 4.3.3), the average and range of soil temperature may not be different from those in the open, or may even be higher for certain periods.

What is also important to plants, is the coincidence of daily and yearly soil temperature patterns with surface temperature patterns since different plants have optimal water uptake for transpiration at specific soil temperatures (Gindel 1973). The lag period in the daily and yearly soil temperature regimes compared to air temperature regimes is likely to differ between open sites and scattered woodlands.

4.5 Conclusion.

The microclimatic influences of trees are likely to vary with a multitude of factors which have to do with the topography, with
the seasonal and daily climate, with the size and other characteristics of the trees, with the soil and pasture plant characteristics. Generalizations on the magnitude or indeed the qualitative effects of woodland such as "an adequate stand of trees and shrubs will protect a given area against extreme and unfavorable climatic effects" (Von Maydell 1977); "as a rule windbreaks even out extremes of temperature" (Deiwaulle 1977) (both authors referring to semi-arid zones) are therefore often incorrect.

Without a detailed understanding of the microclimatological process which have lead, at a specific site for a specific year, an association of pasture with trees to a better or worse production than pasture outside the zone of influence of trees, it is likely to be unreasonable to predict what the outcome of such an association may be in a different location. This becomes increasingly important in areas where the topography is accidented. The magnitude of the microclimatological influence of the trees and its quality may also vary from year to year: for instance, vegetation under *Acacia albida* in Senegal is at an advantage compared to that in the open if the first rainfall is above a certain intensity, but a disadvantage in years when the first rain is slight (Dancette et al. 1969 see section 4.3.1). Hence an attempt at quantifying the climatological benefit or disadvantage of the tree/pasture/livestock association for any year, would have to include a measure of the probability of occurrence of certain weather patterns for any one year or groups of years.
Soil Relationships and Allelopathy

It seems logical that, if trees and pasture plants are spacially closely associated, competition for moisture or nutrients may occur when these are in short supply. However, by utilizing the soil resources at different rates in time and/or space, competition for a resource may be reduced considerably. It is also becoming increasingly clear that some species grow better when in association with certain other species, whether the association is synchronous or whether it is sequential; in other situations, negative interactions occur which cannot be explained by direct nutrient or moisture influences (e.g. allelopathic influences).

The nature of such relationships is of direct consequence to immediate production and, through their influence on ground cover, also of consequence to the long term production potential by providing varying protection to soil surfaces (limiting or enhancing soil erosion or leaching).

Interactions between plants in the soil zone are due to a combination of the factors mentioned above, and there is usually also a relationship between moisture, nutrient and allelopathic interactions (Oelshagle et al. 1976); for instance, higher nitrogen soil concentrations due to the presence of an N\textsubscript{2} fixing legume may enable the roots of a plant which does not fix N\textsubscript{2} to grow deeper into the soil where more moisture may be available; or the soil water holding capacity may be increased to the benefit of pasture plants by the extra humus provided by a tree.
component – such as in the case of blue oak (*Quercus douglasii* hook & Am.) in the coastal ranges and Sierra Nevada of California (Baker 1978). Nevertheless, for the purpose of clarity, the water, nutrient and allelopathic interactions are dealt with separately. The examples have been chosen to illustrate the range of interactions which may be found in tree-pasture complexes.

5.1 Soil moisture interactions.

A major problem in the study of soil moisture (and also nutrient) interactions between trees and herbaceous plants lies in correlating the observed experimental results on moisture regimes with plant responses in a realistic way. The potential water available to plants (available water holding capacity) is the amount stored between field capacity and permanent wilting point. However these can vary by a factor of 10 or more between different soils (Jackson 1977). Since soils can vary significantly with depth and laterally, an average percentage moisture (by volume of soil – a measure often used) for the rooting zone or zones is not likely to realistically indicate the amount of water available to plants. Further, since the soil structure of a pasture (and therefore its available water holding capacity) can be considerably altered by the presence of trees (see section 5.2), comparisons of the percentage soil moisture under a treeless pasture with that of a pasture with trees cannot necessarily be directly related to differences in water availability. Nevertheless, investigations which have used percentage soil moisture as a comparative measure of
the water available to plants are still referred to since in many instances, the differences are nevertheless likely to be indicative of differences in availability.

Many investigations do not give an indication of the replicability of their results and the variation which can be expected: e.g. only one soil sample for each site to be compared, once in the year; no mention of sample size; no exact description of the location of the sampling site in relation to tree canopy or bole. The results of some such investigations are still quoted to illustrate a point or when other evidence tends to support the plausibility of the results found.

5.1.1 Indirect effects.

While indirect effects of trees on relationships between pasture plant, soil and water and vice versa (such as altering soil structure as mentioned above) are always likely to be of some importance, there are some situations in which such effects can be particularly significant to production.

In areas where a high water table associated with saline subsoils leads to decreased pasture productivity because evaporation and capillarity concentrates salt in the surface layers, a certain density of trees may be able to lower the water table so as to reduce surface salinity concentrations and enable more productive pasture plants to grow. Such a problem was caused by forest clearing and its subsequent solution by partial reafforestation is being implemented in large affected areas of Western Australia (McKinnel et al. 1978, CSIRO 1978).

The rooting depth of pasture plants may be increased by
the presence of trees through the lowering of the water table and improvements in soil structure at depth. On a low humic gley in Bahia in Brazil, Zevallos et al. (1967) found that Poro trees (Erythrina glauca) improved the rooting depth of cocoa trees through a draining effect. The improved soil structure may improve the infiltration and percolation of rainfall into the larger volume of soil occupied by the roots of pasture species. This could be beneficial both in parts of the wet tropics (Apolo 1979) and in more temperate regions where the frequency of moisture deficits can be increased due to the shallow rooting zone caused by impervious soil layers, even in relatively high rainfall areas such as the Southern Uplands of Scotland (Caborn 1971). In wet upland Britain, an improvement in soil structure and rooting depth can be achieved by some tree species. There is increasing evidence that some trees such as Betula pendula and B. pubescens are able to reverse the podzolization process (Miles 1978, 1981), or may help improve the rooting depth in some gleyed soils (e.g. Alnus spp., Bradshaw 1980; Pinus contorta Dougl. ex Loud., Pyatt et al. 1979). The draining influence of poplars (Populus spp.) in pastures is appreciated by farmers on some badly drained soils in the Segala and Levezou (Tarn and Aveyron, France, Pers. observation). Anderson (1978) also suggested that in pastures which are subject to production losses through winter waterlogging in Western Australia, improved yields may occur when trees are grown and water tables lowered.

5.1.2 Direct effects.

As Sanchez (1976) suggested in an appraisal of present
knowledge on multicropping systems, the largest gap, by far, is our lack of understanding of the relationships between plants below the ground. The rates of water uptake vary with age, and the period of maximum demand for water (and nutrients) for one species may not coincide with that of another (Oelglé et al. 1976). Further the degree of effective overlap between intercrop components' root systems may vary in time and space, and a knowledge of the distribution and density patterns of the roots of intercrop components is essential, along with a knowledge of the relative availability of soil resources in each zone. Competition for moisture is effective over a greater volume of soil per unit surface area of roots than for most nutrients, the depletion zone can extend up to 25 cm from a single root depending on the hydraulic conductivity of the soil (Trenbath 1976).

In areas of the world where frequent soil water replenishment occurs, competition for moisture between a tree component and grassland component may be of little consequence to their respective production (e.g. Alnus acuminata planted in pastures in Costa Rica - Holdridge 1951).

However in many parts of the world, there are one or more periods of varying length during which low soil moisture levels are limiting production. It is in such situations that a good understanding of the spatial and temporal requirements for soil moisture by both the tree/shrub component and the pasture component, and a good understanding of soil water replenishment in different root zones at different times are crucial for the appropriate management procedures to provide the maximum production of either component or a component mix. In some arid and semi-
arid zones, the impact of scattered trees on the moisture regime of rangelands, and therefore on the grazing production potential is strongly disputed. Foresters sometimes claim that little detrimental influence occurs while some even claim that "tree plantations are able to raise the entire water table over a wide area, thus bringing the possibilities of conventional agriculture to regions where such activities had been considered out of the question" (Sholto Douglas et al. 1980 p 6 - 7); others suggest that moisture competition by even a few trees or shrubs per ha is significantly detrimental to pasture production - e.g. *Prosopis* spp. in the semi-desert range areas of the South Western U.S.A. (Martin 1975). A few situations are therefore discussed in some detail.

i) Douglas Fir (*Pseudotsuga menziesii*) in Oregon (U.S.A.)

In the Oregon Coastal Ranges which experience a warm low summer-rainfall climate, Preest (1977) found a strong positive correlation between available soil moisture and weed control, and a strong negative correlation between moisture stress in trees and available soil moisture with an associated significant influence on Douglas fir (*Pseudotsuga menziesii*) growth during the first years of establishment. Similar results had been found in Oregon by Hall et al. (1959) and Hedrick et al. (1966). The higher soil moisture levels found when weed was controlled must have been due mainly to the removal of soil moisture competition by the weed roots since little rain falls during the summer, while the soil moisture levels were broadly similar prior to the dry period in both weeded and control plots (i.e. no pre summer differences occurred due to weed interception loss).
ii) Pinus ponderosa in Western U.S.A.

Strong competition for soil moisture also restricts root development and total growth of young Pinus ponderosa (Laws) on the west side of the Sierra Nevada (California) where precipitation levels during the summer growing season are low (Burcham 1965). The grasses are said to compete better than the pines for the available moisture and below a critical level may die after having completed their life cycle or become dormant, while pine is less drought resistant. As Rindt (1965) suggested, this competition is most critical until the tree roots have grown beyond the zone of competition and moisture deficit.

Near Flagstaff (Arizona - low precipitation May to July), Larson et al. (1969) investigated the competitive advantages for moisture of the two main grasses, Arizona fescue (Festuca arizonica Vasey.) and mountain muhly (Muhlenbergia montana Nutt. Hitch.) over those of Ponderosa pine seedlings in 3 sets of plots (pine + each grass species and weeded pine plot). Although the roots of both grasses grow 50% faster than those of pine, since fescue roots start growing in mid April, one month before those of pine and muhly, fescue has a more detrimental impact on pine growth. Further fescue reduces the soil moisture potential at the 10 cm depth to or below -15 bars twice each growing season, while muhly reduced it to that level only once, and pine alone kept the soil moisture potential above that level throughout the year. The roots and shoots of the grasses resumed growth quickly after the late spring drought, while the roots of pine remained dormant. The result of such competition led to significantly higher pine needle moisture contents during the dry period for weeded, compared to grassed plots. Pine seedlings
after 2 years on weeded plots showed an eleven fold greater net gain in dry weight than those grown with grasses. The dry weights of roots and shoots of pine grown in grass were over 4 times smaller ($P < 0.05$) than those grown without grass competition. However the net dry weight gain of pines growing with muhly was over 4 times that of pines growing with fescue. Since the roots of watered pines elongated as rapidly in plants associated with grasses as those without grass and not watered, the competitive factor is likely to be moisture (rather than inhibitors produced by the grasses - see section 5.3).

However the soil moisture remained high below a 40 cm depth for all 3 plots with few grass roots occurring below this depth while the main roots of the surviving pines extended below the 40 cm depth. The extent to which older pines and grasses can grow on the same site without competing with each other for moisture to any considerable extent depends on several factors. Where the soils are deep and of a suitable structure, Ponderosa pine roots may reach 2 m or more depth (Schubert 1974). Where the pattern and intensity of precipitation is such that the soil moisture replenishment in the pine rooting zone is not significantly reduced by the drying power of the grasses, and the latter's roots remain in the surface layers, little competition between grasses and pine trees would occur. On the other hand in shallow rooting soils and/or where most precipitation occurs as small rain events and the rain predominantly replenishes only the grass rooting zone, competition would effectively occur. However since Ponderosa pine roots may extend laterally to 30 m and generally extend to 70% of the tree height beyond the edge of the crown, soil moisture competition is strong between
trees in dense stands (Schubert 1974), particularly where
droughts occur during part of the growing season. The inter-
tree competition can be such that young stands grow very slowly:
from Schubert's (1971) study on periodic annual increments of
Ponderosa pine stands of various residual densities, it would
seem that inter-tree competition for moisture starts occurring
at a growing stock level index of 13.8 m² ha⁻¹ (in that study
equivalent to 570 x 43 year old trees ha⁻¹ with an actual stand
basal area of 6.9 m² ha⁻¹).

iii) Larch (*Larix decidua*) in the Alps (Europe).

In some areas of the Alps which experience long dry periods
during the summer season, scattered larch (*Larix decidua*) have
been found to be beneficial to soil surface moisture and pasture
production. Where the larch can root deeply and rely on soil
moisture stored since the spring melt, little moisture competition
with pasture plants occur, and the improved microclimate combines
to reduce soil moisture deficits. These benefits have been reported
for the Brianconnais (France) (Poncet 1954) and south facing
slopes of the Valais (Switzerland) (Hieben 1957, Kuonen 1980).

iv) *Eucalyptus globulus* in Ecuador.

In parts of Ecuador, *Eucalyptus globulus* is sometimes
introduced on pastures (*Pennisetum clandestinum*) but the
alleged strong competition for moisture by the Eucalypts
during the dry season leads to pasture dormancy and an end to
growth at an earlier stage than on treeless pasture (Lojan 1979).

v) Poplar in France.

In a detailed study of intercropping with poplars (*Populus
tree americana* 1214) in various parts of France, Barneoud et al.
(1979) found that the nature and extent of the moisture mediated
influence by the ground crop on poplar growth varied with soil
types, local climate and the type of annual crop used. In the hot and dry summer of the South of France, competition by the crop is detrimental to poplar growth unless the water table is accessible to the tree roots. On suitable soils in other areas, grass production (e.g. "ray grass") has a negative influence on poplar growth because its high demand for water occurs at the beginning of the growing season (May - June), coinciding with the time of highest water demand by the poplar. Hence autumn cereals are not encouraged while spring crops such as maize, and feed or grain spring barley are encouraged as their time of high water demand occurs after that of poplar.

vi) Coconut in several Tropical climates.

Coconut (Cocos nucifera) plantations often have an undercover of pasture. Investigations in India, Sri Lanka and West Africa on the influence of pasture on coconut soil water relations have shown that the nature (positive or negative) and degree of the influence also varies with the precipitation regime, depth and type of soil, the species composition of the pasture and the age of the coconut trees (Santhirasegaram 1966, Ohler 1969, Steel et al. 1974).

vii) Pinus radiata in Australia and New Zealand.

The influence of pasture on the soil moisture regime of Pinus radiata also varies according to conditions though is usually considerably detrimental to young pines and was discussed by McKinnel (1974, 1979) for Western Australia on red loam soils, Squire (1977) for North East Victoria on heavy soils, and Knowles et al. (1973) for New Zealand. McKinnel (1974) suggested that the pines are subjected to strong competition by grasses until the tree canopies close.
Farnsworth et al. (1976) in New Zealand found that although the soil moisture in pastures in Pinus radiata plots (see section 4.2.2 for site characteristics) was not replenished as much as in a tree-less plot, the moisture retention was greater in planted plots and therefore led to greater concentrations of soil moisture in tree plots following a certain period without rain. Anderson et al. (1979) during some dry years in Western Australia found that the soil moisture content of pastures with P. radiata (density 143 - 261 stems ha$^{-1}$, height 13 m) was always higher from September to February (in the top 10 cm of soil) than on an adjoining tree-less pasture — highly significantly so (P<0.001) by 10% (difference of 23 and 33% moisture by weight) for 6 weeks and significantly so (P<0.05) by 8% for a further month. The soil moisture under trees also remained above clover wilting point (c. 15% moisture) for c. 2 weeks longer under trees than in the open. Clearly the combined evapotranspiration of trees and pasture is lower in mixed plots in these examples than in open pasture.

viia) Savanna in Zimbabwe.

In Zimbabwe, near Fort Victoria, Kennard et al. (1973) found that following soil moisture recharge, the soil moisture at 15, 45 and 60 cm depth was depleted fastest on sites with pasture associated with a closed tree canopy, slowest on sites with an open tree canopy — the open pasture site showing an intermediate position. The rapid loss of water from sites under closed canopies was assumed to be a result of the greater rate of transpiration of trees. The considerably lower soil surface temperature found in open canopy sites compared to open grassland sites suggested that the lower rate of soil moisture depletion in the former is likely to have been due to reduced
evapotranspiration from the pasture layer since the yield of the herbaceous layer was 48% greater in open canopy sites than in open grassland. The herbaceous layer was mainly composed of *Panicum maximum* and the tree component of *Brachystegia spiciformis* and *Julbernardia globiflora*.

viib) *Anacardium occidentale* L. and pasture on the Kenya coast.

Goldson (1973) found that the rate of soil moisture utilization down to a depth of 1.5 m was much more rapid in open pastures than in pastures with cashew trees at 10 m spacing. The cashew was found to extract soil moisture from depths of at least 4 m. More water was also extracted in open grassland to a depth of 1.5 m and the better soil moisture regime found during at least part of the dry season in the pasture associated with cashew trees was given as one factor contributing to its considerably lengthened period of pasture growth during the dry period compared to the tree-less pasture. Considering that cashew yields have been found to be reduced by inter-tree competition for moisture, the overall production efficiency of a system with widely spaced trees and pasture was suggested to be improved. The possibility for such a system to be more productive and for the pasture not to compete with well established trees would seem to rely on heavy seasonal rains which enable a complete soil moisture recharge beyond the pasture rooting zone.

viii) *Prosopis* spp. in the S.W. U.S.A.

Martin (1975) suggested that even moderate stands (c. 60 stems ha\(^{-1}\)) of mesquite (*Prosopis* spp.) can reduce herbage production by half in the large semi desert ranges of the S.W. U.S.A., mainly because of the long lateral roots which spread between trees/bushes. He
claimed that mesquite requires 3-4 times as much water as native perennial grasses to produce a unit of dry matter and therefore suggested that mesquite invasion is detrimental throughout the semi desert range area; mesquite having to be cleared to restore the ranges to full productivity.

Cable (1977) investigated in detail the seasonal use of soil water by sparse velvet mesquite (*Prosopis juliflora* var. *velutina*) stands (c. 50 mature trees ha$^{-1}$) near Tucson (Arizona). The rate of soil moisture recharge and use was measured to a depth of 6 m at six points beneath tree crowns and up to 15 m beyond the crowns in clearings; all other vegetation in the vicinity of the sampling holes was killed, and 4 trees were killed to measure the difference in water recharge and use in the absence of trees (i.e. water loss from areas cleared of trees due to seepage and evaporation). The gravelly sandy loam changed to a gravelly clay at 2.5 to 4 m depth and since little soil moisture recharge occurred below 3 m, the water regime in the top 3 m only was described. The soil moisture was expressed in terms of "volume percent available" - i.e. that in excess of the permanent wilting point of mesquite (which does not necessarily coincide with the percentage volume of water available to annual or perennial grasses). Yearly precipitation is highly variable: recharge precipitation for the winter of 1970-1971 was less than 50% of the long term average, while that for the 1971-1972, 1972-1973 winters was 124% and 183% of the long term average respectively. The area is subject to winter and early summer precipitation, and to a late spring and late summer drought.

Water recharge reached a maximum depth of 3 m, highest in the top 25 cm and decreasing with successively greater depth.
However during the summer recharge, high evapotranspiration rates prevented recharge below 1 m. It was found that soil water is extracted most rapidly where and when available soil water values are highest. Immediately after precipitation, extraction rates by mesquite are highest next to the trunk and up to 10 m beyond the crown edge, rates being generally similar over this distance for a given depth and similar amount of available soil moisture. Following recharge, extraction is therefore highest at shallow depths, the major source of water for perennial and annual grasses. Successively greater depths are added to the water supplying layer as the growing season advances. During dry periods, and of particular importance during dry years, when moisture recharge has been insufficient for the mesquite close to the tree, the competition for moisture extends to at least 15 m beyond the crown edge.

Tiedeman et al. (1971) referred to studies which have found significant increases in the moisture content of the upper 45 cm of soil at distances of up to 10 m from killed trees compared to live trees. Further when the mesquite trees had been killed, soil moisture was available for longer periods of time than where trees were alive. Tiedeman et al. (1977) found that the removal of *Prosopis juliflora* (Swartz D.C.)1 (distant from other trees by at least 30 m) on a similar site in the same area as that used by Cable (1977), did not show a marked change in soil moisture status over the year and at different depths up to 6 m away from mesquite trees between sites cleared of mesquite and undisturbed sites (although they admit that the

1 It is uncertain whether this is the same species or variety as that mentioned by Cable (1977). *Prosopis* taxonomy is still rather confused (Leaky 1981).
lateral roots of live mesquite trees 24 m or more away may have influenced the moisture regime. They suggest that the eradication of mesquite only increases the amount of water available to grasses which increase their vegetative cover and therefore water consumption.

ix) *Prospis spp.* and other species in dry zones of India.

On a site in arid Western Rajasthan (India) (average annual rainfall 366 mm), Lahiri (1975) found that although the soil moisture to a depth of 180 cm remained close to permanent wilting point during the dry season (October - mid July), *Prosopis cinneraria* trees could tap water from moist layers to a depth of more than 10 m.

Near Bellary (Karnataka - India) (average annual rainfall 508 mm - 50% of which falls during September and October), Prajapat Ji et al. (1971) suggested that considerable direct competition occurred for moisture by the roots of a *P. juliflora* shelterbelt with *Sorghum vulgare* roots up to a distance of about 28 m from the shelterbelt (4 times its height) at depths of 0 - 20 cm and 20 - 40 cm. However at c. 30 m, root competition for moisture became less severe and the *Sorghum* roots were able to extend into the 20 - 40 cm soil depth zone where moisture was available.

Near Johdpur (Rajasthan) (annual precipitation highly variable) several studies on the soil moisture relationships of various tree species and grasslands have been carried out. Aggarwal et al. (1976) compared the available water capacity (difference between moisture retained at 15 bar from that retained at 1/10th bar tension) in November (the end of the rainy season) at 6 levels down to 90 cm soil depth for 5 desert tree
species (Prosopis cineraria, Prosopis juliflora, Tecomella undulata, Albizia lebbeck and Acacia senegal) (12 year old and 2.4 m spacing) and a treeless plot, all on a similar soil. Slightly lower available water capacity had developed under Albizia lebbeck, Prosopis cineraria and Tecomella undulata compared to soils under Acacia senegal which had a similar capacity as treeless sites. On the other hand, the percentage moisture content at the time of sampling was highest under Tecomella undulata (average for all depths 3.9%), intermediate for the treeless sites (2.97%) and lowest for P. juliflora (2.5%). However there were considerable differences in the way these variations in total moisture percentage were distributed in the 6 depth zones, as indeed there were considerable differences between depths for available water capacity, though there seemed to be no correlation between the two moisture related characteristics.

Gupta et al. (1978) described a further study on soil moisture changes down to 120 cm depth under the same tree stands when they were 15 years old (unfortunately there was no comparison this time with the treeless site). The measurements were taken regularly over 2 successive years during which precipitation was 244 mm and 622 mm respectively. Throughout the period of observation, the total profile (120 cm) moisture content was highest under Tecomella undulata followed closely by that under P. cineraria; P. juliflora had the lowest while the other two had intermediate levels. Although between December and April (dry period) not much difference in soil moisture content occurred between sites under different species (because depletion was probably complete), in October of the dry year,
the profile moisture content was 50 mm for *P. cineraria* and *T. undulata* and only 30 mm for *P. juliflora*; in July of the wet year, it was 115 - 130 mm for the two former species, and 55 mm for *P. juliflora*. Although they tentatively suggested that these differences may be due to the rooting habit of *P. cineraria* and *T. undulata* to depths below 1.2 m, there is also the possibility of differences in total moisture demand by different species which could explain part of the observed differences in moisture storage. Nevertheless *P. juliflora* had the maximum level of percentage moisture (by volume) in the top 30 cm of soil during the 2 years while the minimum occurred under *T. undulata* and *P. cineraria*. However this situation was reversed at lower depths where *P. juliflora* depleted soil moisture to a much greater extent than other species. These differences may be explained by the greater observed production of the herb layer under *T. undulata* and *P. cineraria* canopies compared to that under *P. juliflora*. Since the site was on a flat alluvium plain, a water table may have existed within reach of the roots of some of the tree species, which may be replenished partly by precipitation occurring outside the site. It is therefore not reasonable to believe that such soil water consumption patterns could be replicated on different sites.

x) **Acacia albida** in the Sahel.

In the Sahel various tree species shed their leaves during the rainy season and put out new leaves at the start of the dry season. Their demand for water therefore has only a small overlap with that of pasture plants.

Near Bambey in Senegal (summer rains) Charreau et al. (1971) found that on sandy soils *Acacia albida* have roots down
to 15 - 20 m depth reaching the water table, and no lateral
roots in the first 1 - 2 m of soil depths. In mid October, 15
days after the end of the rains, a crucial period for understorey
plant development, the significantly higher (P < 0.001) soil
humidity in the top 10 cm under the trees compared to away from
trees enabled better understorey plant nutrition and growth
(Charreau et al. 1965). Dancette et al. (1969) had found in
the same area a better soil moisture conservation in the top
1.3 m of soil after the end of the rainy season under Acacia
trees than on treeless sites. Similar results were found under
Acacia albida in the Jebel Narra region of Sudan by Hadwanski
et al. (1967). The greater precipitation input under canopies
(see section 4.3) is likely to contribute to the improved soil
moisture under the trees.

xi) Australian rangelands.

Large areas of semi arid and arid rangelands of Australia
support trees in stands of varying density which are reported
to have varying impacts on the soil moisture regimes of the
herb layer. Story (1967) provides an example of good circum-
stancial evidence indicating that sparse pasture around trees in
large areas of Australia was due to moisture competition by
the trees. In areas of low rainfall, the bare areas corresponded
to the radial spread of roots (to from 8 to 60 m beyond the tree
canopies) of several species of Eucalyptus, Acacia and others.
Yet in wetter areas at higher altitude, the density of ground
vegetation in the circles increased to levels found where trees
had been removed. However a detailed study of soil moisture
regimes at different depths to 1.2 m during the year inside the
circles, in areas where trees had been removed and in dense
pasture away from trees, showed that competition for water was unlikely to be the reason for the sparse grassland vegetation associated with trees.

In the large mulga (*Acacia aneura*) pastoral zones, mulga and *Eucalyptus populnea* trees are said to be detrimental to pasture production due to their competition for moisture. Wilcox (1960) found over 3 years in an area of Western Australia that mulga removal increased total green production (ground production + mulga pods and leaves when mulga present) by a factor of more than 2; this was attributed to greater soil moisture availability which also enabled the ground flora to respond to rain more quickly on cleared sites and to remain available for a longer period after the end of rainy periods.

More detailed studies on the effects of mulga on soil moisture regimes were carried out by Pressland (1975, 1976a) near Charleville (S.W. Queensland). The soils are 1 - 2 m deep lateric red earths underlaid by ironstone gravel; they have a reasonably uniform water holding capacity down the profile. Precipitation variability is the most important climatic factor in the area, and may fall in any month or not at all although yearly averages are 467 mm (Burrows 1978).

Soil samples were taken regularly for 2 years from each 15 cm horizon to a depth of 135 cm at different distances from tree boles in mulga stands which ranged in density from cleared areas (0 stems) to 4000 stems ha⁻¹. Evapotranspiration was calculated by solving the soil water balance equation

\[ E_t = P - (S_1 - S_2) \]

where \( E_t \) = evapotranspiration, \( P \) = precipitation over a set period, \( S_1 - S_2 \) is the change in soil moisture storage between different dates (run off and deep drainage were ignored...
in this area as they were found to be insignificant). The combined interception and evapotranspiration value increased steadily from cleared areas to 4000 stems ha\(^{-1}\), while soil moisture levels were highest at most samplings on cleared sites, and lowest on sites with high stem densities. *Bulga* is known to extract water held at potentials higher than -120 bars. Some of the pasture species can probably not extract water at such potentials; the crucial point is therefore that because of the very variable precipitation regime, the fewer trees there are, the greater the probability that soil moisture levels will be above the level limiting growth for long enough periods to enable pasture plants to grow or at least remain green.

5.1.3 Genetic variability and water use efficiency.

It seems that the genetic variability in water use efficiency (\(\frac{\text{weight of water used per unit weight of dry matter produced}}{\text{weight of water used per unit weight of dry matter produced}}\)) in different semi-arid tree species may be large (and in tree species and pasture species from moist tropical and temperate zones - see section 2.3). Felker (1979) referring to different results of yields of *Prosopis* spp. on sites with different annual precipitation, found a water use efficiency for *Prosopis juliflora* in Arizona of 1730 kg water/kg dry matter accumulation; in another location, *Prosopis* spp. dominated savanna had a water use efficiency of 250 kg water per kg dry matter. In a semi-arid area of West Pakistan different *Prosopis* accessions (incl. some of *P. cineraria*) showed a variability in efficiency ranging from 205 to 19700 kg water/kg above ground dry matter. There would therefore seem to be much potential for selecting genotypes
which transpire more or less according to one's requirements in an tree-pasture combination.

However such calculations, and the kind of extrapolation which one could make from Gupta et al's. (1978) data on the relative merits of planting different species in terms of differences in patterns of water use, may be unreasonable if the water table contributes to the water requirement of the species concerned - the ground water may be fed by precipitation occurring outside the area. *Prosopis* spp. roots have been found at depths of 80 m (Felker 1979) and in Southern California in an area of low annual precipitation (100 mm) *Prosopis* spp. was found to be 60 - 90 cm tall when the water table was 14 m deep, while 3.6 - 6 m tall when the table was 3 m deep.

5.1.4 Conclusion.

An intimate mixture of tree and pasture does not necessarily lead in all situations to a level of growth reduction in both the tree and pasture components which is proportional to the quantities of water used by each; i.e. that amount of water not being available for the other component.

The sampling programme and intensity needed to work out tree pasture moisture relationships has to take into account the possible spacial variations in precipitation reaching the ground (see section 4.3) which can vary considerably both quantitatively and qualitatively from year to year. The demand for water by plants is influenced by the climate and therefore the water use efficiency may differ for a pasture growing with trees scattered amongst it and one without.
Differences in rooting depth between the tree and pasture component reduce the competition for water if the trees can rely on the water table or if the rain events are large enough that the rooting zone of both the pasture and the tree component are replenished. Detrimental competition therefore often occurs when trees are young and their roots are shallow. The timing of maximum demand for water may vary between the pasture and the trees.

In some years or parts of years which are dry, the competition for water may be particularly detrimental (e.g. *Prosopis juliflora* var. *velutina* in the S.W. States, Cable 1977; *Eucalyptus globulus* in Ecuador, Lojan 1979) while for other areas it is under such conditions that the mixtures are particularly useful (e.g. *Larix decidua* in the Alps).

The degree of competition between tree and pasture therefore depends on the general climatic pattern and the specific pattern each year; the soil type and depth and whether a water table is within reach of tree roots; the species and ecotypes used in the intercrop mixture. Therefore species which do not compete much on a particular site may do so on another site, while on a given site some species mixes are more appropriate than others. The role of selection for more water efficient genotypes is likely to be of particular importance to tree-pasture moisture relationships.

5.2 Soil nutrient interactions.

The use of trees to improve soil structure, soil nutrient retention capacity and the total nutrient status of poor, degraded
or easily leached sites has been advocated by a number of publications for the humid tropics, the arid zones, acid grass savannas and tropical upland systems (e.g. Bene et al. 1977, King et al. 1978, Steinlin 1979); the idea has been revived recently for acid upland moorlands in Britain (Ailes 1981).

The rationale is that superficial roots of trees reduce nutrient and soil losses from leaching and erosion, and their deeper roots bring up nutrients either leached to lower depths, or recently released by weathering (Lundgren 1979). However, as King et al. (1978) noted, the studies which have been carried out on the merits of trees as fertility maintainers or improvers appear to give conflicting results. Fried in the discussion of Pratt's (1979) paper on soil research in Agroforestry suggested that there is very little hard data on the subject of the "nutrient pump" characteristic of trees.

The role of herbaceous vegetation on the nutrient status of tree crops also varies from being beneficial in some cases to detrimental in others (Pritchett 1979).

A look at some studies on the subject should outline the factors which are involved in the relative merits of trees to pasture nutrient status and vice versa.

5.2.1 The influence of trees on pasture plant nutrient regimes.

- Indirect influences.

An improvement in rooting depth (see section 5.1.1) should enable roots to have access to more nutrients because of the larger volume of soil tapped.

The nutrient retention capacity of any layer of soil is
influenced by several factors including: the soil layer's organic content and the chemical nature of the organic compounds; the size distribution and type of mineral particles - i.e. the proportion and type of sand, silt and clay; the pH and the rate at which water passes through the soil layers either downwards or upwards, which in turn is influenced by some of the above factors.

The organic content (total C) of the top soil layers is generally increased underneath trees in pasture or rangeland if the litter layer is not removed as it falls (e.g. by wind or people) and if it can break down readily (e.g. does not accumulate as dry matter during the dry season and then burn with natural or man made fires). Kennard et al. (1973) found in Panicum maximum pasture on sandy, inherently infertile soils in Zimbabwe, that on an open grassland site, the organic carbon content of the top 15 cms was 0.6%; on a site with an open tree canopy, the carbon content was 1.9% and with a closed canopy 2.2%. Part of the accumulation of organic matter under canopies may in some situations be due to preferential deposition under the canopy of airborne organic matter (e.g. under Prosopis spp. in the desert grassland ranges of the S.W. U.S.A., Tiedemann et al. 1973).

The soil can contain different organic matter concentrations under different tree species on the same site. Singh et al. (1969) found a considerably greater amount of organic carbon in the top 60 cms under Prosopis spicigera Linn (also called P. cineraria) compared to that under Acacia arabica (both tree species approximately 30 years old) and that on open sites near Udaipur (India) in November. Although they suggested that such
a difference may be due to the greater vegetative production of the former species, other factors such as differences in the rate of breakdown and microbial respiration under the 2 species due to other factors may be at least partly responsible.

Aggarwal et al. (1976) also found differences in the depthwise distribution and total organic matter under different tree species and on a tree-less site near Jodhpur (India) (see section 5.1.2 for details of site layout). In the top 15 cm, the percentage organic matter varied from 0.37 (tree-less site) to 0.57 (Prosopis cineraria); such differences could however be also due to considerable differences in understorey production noted under the different tree species; without more detailed experimentation there is a difficulty in discerning what is the cause and what is the effect of the relationship.

At the other extreme, critically high levels of organic matter occur on acid moorlands such as in the U.K. uplands which receive a high precipitation. The high C:N and C:P ratios at which nutrient immobilization and deficiencies occur, can be decreased under birch. The improved nutrient status and higher pH under birch (Betula pendula and B. pubescens) led to a decrease of the organic matter in the top 5 cms from 194 to 97 g dm$^{-3}$ from a heather (Calluna vulgaris) site to an adjacent 90 year old B. pubescens site in Morayshire (Scotland) (Niles 1981).

The pH of acid and alkaline soils can be improved by the presence of certain trees. On the heather site in Morayshire, the pH improved gradually from 3.8 under heather with the increasing age of B. pubescens to 4.9 when the birch was 90 years old (Niles 1981). Kennard et al. (1973) on their site in Zimbabwe found that the average pH was 5.0 on open grassland
sites and 6.0 in open canopy sites. Singh et al. (1969) found that soil pH at the depth zones 0 - 30 cm and 30 - 60 cm under *P. spicigera* Linn. was 1 point or more lower than that under *Acacia arabica* or a treeless site which had pH values of 8.4 - 8.8.

The influence of *Eucalyptus populnea* on the pH of lateritic clay loams and loamy sands in S.W. Queensland was found to vary between sites. E., N. and S. of Charleville, pH differences (in the top 3 cm) between open ground and under trees were not significant, while W. of Charleville, the mean pH (24 trees) was 6.6 under the trees compared to 7.2 in open sites and the difference was highly significant (Übersohn et al. 1965).

Clearly the soil water infiltration and holding capacity, which is usually improved by an increase in organic matter, indirectly determines the rate at which nutrients are lost by leaching. Under high rainfall for example, nitrates may move past the rooting zone in soils which retain low amounts of water.

5.2.2 Direct influences.

Nutrient influences.

The total nutrient balance of a soil is determined by the rate at which the various elements enter the soil:

i) from the atmosphere in precipitation or in aerosols (Hiller 1979);

ii) by atmospheric nitrogen fixation;

iii) from litter fall;

iv) through weathering of the subsoil;
and are lost from the soil by:

v) leaching; vi) volatilization; vii) the build up of nutrients in biomass.

Man can also add nutrients to and remove them from the system by cropping standing biomass.

Trees are only likely to have a considerable influence on ii), iii), v) and vii) of the above although they can influence iv) to a certain extent for some elements - e.g. by acid phosphatase activity in the roots or mycorrhizae. Their role in the redistribution of nutrients both vertically and laterally may be particularly important. Kellman (1979) based on work in open savanna in Belize suggested that the reason for preferential nutrient capture by savanna trees was unspecified but suggested that it was likely to be from preferential capture of precipitation inputs.

Distribution of nutrients (excluding N. fixation effects).

On a low humic gleys in Bahai (Brazil) Zevallos et al. (1967) found that the nutrient levels in soils near *Erythrina glauca* trees in a cocoa plantation were higher than away from the trees. Similar results have been found from a number of situations in different climatic zones. The phosphorus and nitrogen in the surface layers of pasture soils are higher under Blue oak (*Quercus douglasii*) than away from the trees in the woodland savanna areas of the Coast ranges and Sierra Nevada of California (Baker 1978). Larch (*Larix decidua*) is said to improve the nutrient status of surface soils both in the Alps (Rieben 1957, Kuonen 1980), and in parts of upland Britain (Borissow 1962). Mineralization of organic nitrogen has been shown to be enhanced by Larch in upland Britain (Carlyle 1984). Larch needles are known to contain a relatively high percentage of P and are readily broken down; this is reflected in higher P contents of the soil (Ovington 1959 quoted in Borissow 1962.). *Larix sibirica* (Lebeb) is also reported to have a litter rich in P and K on a number of sites in Ukraine - improving the growth of Ash
Fraxinus excelsior L.) compared to Ash in pure stands. The richness of the litter is also particularly propitious for the nitrogen exchange of the soil by microbes (N\textsubscript{2} fixation, ammonification and nitrification) (Pogrebnjak 1962).

Miles (1981) found an improvement in the nutrient status of the top 15 cm of soils under birch compared to heather sites on 12 out of 13 sites in the UK uplands. Total P increased from 151 mg dm\textsuperscript{-3} under heather to 240 mg dm\textsuperscript{-3} under 38 year old Betula pendula near Advie (Morayshire). The N mineralization rates (after 14 days incubation) for the same site increased from being negative (-1.3) under heather to 45 mg dm\textsuperscript{-3} week\textsuperscript{-1} under 38 year old birch.

In semi arid S.W. Queensland, on infertile soils, the nutrient status (available P\textsubscript{2}O\textsubscript{5}, exchangeable K) has been found to be considerably and significantly greater under Eucalyptus populnea than in inter-tree areas in the surface soil layers (Ebersohn et al. 1965, Christie 1975, Burrows 1978). The authors do mention, however, the possibility of animals camping underneath trees (Christie 1975), of the concentration of top soil and other organic matter blown under the trees, and of bird droppings (Ebersohn et al. 1965) as factors which may redistribute nutrients under trees. The importance of such factors is clearly highly variable and would depend on such variables as the exposure of the site, the animal and tree stocking densities.

On sandy soils of low inherent fertility in Zimbabwe, Kennard et al. (1973) found that the top 15 cm of soil was markedly richer in exchangeable Mg, Ca and K in grasslands with an open tree canopy and a closed canopy compared to a treeless grassland; however there was little difference in mineral N and
resin extractable P levels between sites.

On a sandy to sandy loam soil near Udaipur (India), soil analysis of samples from 6 depths down to 1.8 m, showed that total profile total N, total profile available P$_2$O$_5$ and total profile available K$_2$O were in considerably greater quantities in a field under *Prosopis spicigera* compared to treeless parts of the field (Singh et al. 1969). Soil samples under *Acacia arabica* (of the same age and configuration as *P. spicigera*) in the same field showed no marked difference with the nutrient status of areas in the open; the differences in total profile nutrient content were mainly due to the large differences found in the top 60 - 90 cm. Near Jodhpur, Aggarwal et al. (1976) found that the soil nutrient status of a pasture varied considerably between a treeless pasture and pasture under various species on the same site. Available N, P and K concentrations in the top 15 cm were medium to high under *Prosopis cineraria*, *Tecomella undulata* and *Albizia lebbeck*, and low under *Prosopis juliflora* and the treeless pasture. Available micronutrient contents (Zn, Mn, Cu and Fe) were also higher under *P. cineraria*. Aggarwal et al. (1976) suggested that the higher nutrient status of soils under *P. cineraria* may be attributed to the higher ground forage production found under this tree species. The relative role of the understorey in maintaining a high nutrient status in the top layers of soil must however depend on the tightness of the external nutrient cycle between pasture species and the top soil layers. There is no evidence of a tighter cycle since lower depth horizons (down to 90 cm) show no impoverishment in the macronutrients under *P. cineraria* compared to other species or the treeless plots.
Radwanski (1969) found that neem \textit{(Azadirachta indica)} improved considerably the nutrient status of the top 15 cm of inherently poor, acid and leached soils near Sokoto (Nigeria) under their canopies for most nutrients; however total P levels were 195 and 118 ppm (mean for two depths) on treeless sites and under neem canopies respectively. Since the P levels are low in leaves and petioles, it is likely that P is stored in other parts of the tree.

Except for the nitrogen status which may be influenced by N\textsubscript{2} fixation by some of the tree species in the above examples, there is no clear indication of where these nutrients are coming from. In cases where the mineralization rates are fast and where leaching from the top soil layers is also fast, differences in the time of leaf fall could affect the timing of variations in nutrient concentrations; further, even for species which lose their leaves at the same time, the rate of mineralization may differ significantly thereby enabling the possibility of differences in nutrient concentration at certain times in different soil layers. Hence an appropriate sampling sequence may be required in some situations while in most examples quoted above sampling was carried out only once and at approximately the same date for different plots within sites.

It would seem logical to assume that trees which root in the surface soil layers to considerable distances beyond the canopy, would in effect impoverish inter-tree areas to the benefit of soils under their canopy. The extent to which this is what is happening in some of the above examples is not known. However it is the conclusion reached by Tiedemann \textit{et al.} (1973) for \textit{Prosopis juliflora} Swartz near Tucson, Arizona; nevertheless
they did not prove this to be happening since they did not compare the nutrient status of a site cleared of Prosopis with an inter-tree area and an area under P. juliflora canopies.

In the case of mulga (Acacia aneura) woodland and pasture in semi-arid Australia, Burrows (1978) suggested that the mulga grassland is much less efficient in its utilisation of scarce phosphorus than endemic woodlands and that because of the relatively poor ground flora and the large volume of surface roots, the mulga community operates on a very tight external cycling of nutrients. It seems reasonable to assume that mulga trees are likely to absorb nutrients from a wide area in the soil beyond their crown just as they do for water (see section 5.1.2).

The same kind of redistribution of nutrients from a large volume of soil to the top soil layers underneath the tree canopies is asserted by Charreau et al. (1971) for their poor sandy sites near Bambey (Senegal). They suggest that the soil nutrient improvements under Acacia albida noted by Radwanski et al. (1967) on more clayey soils in Sudan and by others in Niger and Mali are caused by a similar redistribution. However there is a significant difference between the soil nutrient improving characteristics of Acacia albida and that found with other trees. Since the roots of A. albida - at least on the sites studied - occur below those of grassland species, the Acacia tree does not compete with the herb layer for nutrients but actually provides a net gain for the understorey production by enabling the absorption of both nutrients which have newly been made available by the weathering process and those which have leached from the upper layers past the rooting zone of the
herb layer. Table 5.1, 5.2 and 5.3 show the results of 2 investigations on the annual nutrient additions to the soil. These additions may be significant as shown by increased crop yields (Charreau et al., 1965). The extent to which the concurrence of maximum tree litter fall with the start of the litter breakdown period and the time of nutrient demand by understorey vegetation may lead to nutrient impoverishment in the lower soil zones and therefore to reduced tree production is unknown.

For several reasons including the frequent difficulty of maintaining a balance between herbaceous legumes and grasses in pastures in many regions of the world (see section 2.1.1), and because N is frequently a limiting factor to herbaceous production, there has been a surge of interest on the suitability of introducing nitrogen fixing trees and shrubs in pastures to improve the nitrogen status of poor grassland sites.

Daccaret et al. (1968) found on pastures planted with several tree species near Turrialba in Costa Rica that the tree legumes *Erythrina poepigiana*, *Pithecolobium saman* and *Gliricidia sepium* had higher total N in the top 20 cm under their crown than on a control treeless plot and a plot with Laurel (*Cordia alliodora*).

Similar beneficial impacts of trees on the N Status of pastures have been described by Finol (1978) for *Alnus jorullensis* in Colombia, Combe (1979) for *Alnus acuminata* in Costa Rica, Charreau et al. (1971) for *Acacia albida* in Senegal, Gerakis et al. (1970) for *Acacia senegal* in Sudan, NAS (1977) for *Leucaena leucocephala*. However many other trees and shrubs are incorporated in pastures, without the nitrogen status improvement which is noted being attributed to the likely N fixing ability of the trees (e.g. *Prosopis* spp. in several areas of the world, Felker 1979).
Nitrogen fixers, however, are often high P demanders (e.g. Alnus rubra mixed with Picea sitchensis on a surface water gley in Scotland, Bradshaw 1980; a general comment on legumes, Pritchett 1979), although some such as Robinia pseudoacacia have a low demand for K and P (Davies et al. 1979); Yet others, such as Leucaena leucocephala (N.R.S.1977) and Acacia albida (see above) are likely to extract their P, K and other nutrients from deep soil layers, and therefore would compete for those to a lesser degree with understorey vegetation. Not all the N which reaches the ground in litter remains for uptake by plants; denitrifying bacteria in the soil can convert nitrogenous compounds from litter fall back to nitrogen gas which is lost to the atmosphere; N.A.S.(1977) suggested only 40% of the N in the litter fall of Leucaena leucocephala remains in the soil and can enhance associated crop growth.

Evidence from Arizona (Felker 1979), the Negev (Israel) and Mali (Breman et al. 1977) and other arid and semi-arid regions (Felker et al. 1980a) suggests that in hot arid environments, the herbaceous primary production is often limited by low nitrogen availability and not only by low rainfall (see also table 2.2). The soil nitrogen (and organic matter) contents of semi-arid soils are typically 5 to 10 fold lower than in temperate agricultural soils (0.03% to 0.05% outside the zone of influence of tree legumes in Arizona and Senegal) (Felker et al. 1980b); the high temperatures in the top layers of soil are likely to inhibit nitrogen fixation, and soil moisture levels in the root zone of annual legumes would only enable nitrogen fixation to occur for a limited period each year. In contrast, the nitrogen fixation potential in deeper rooted tree/shrub
Table 5.1. Increase in nutrient status (kg ha\(^{-1}\) of tree canopy area) in the top 10 cm of soil under Acacia albida compared to inter-tree areas (Bambey - Senegal - From Charreau et al. 1965).

<table>
<thead>
<tr>
<th>Nutrient status</th>
<th>Total exch.</th>
<th>exch.</th>
<th>exch.</th>
<th>total</th>
<th>available</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>Ca</td>
<td>Mg</td>
<td>K</td>
<td>P</td>
<td>P</td>
</tr>
<tr>
<td>kg</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>460</td>
<td>471</td>
<td>95</td>
<td>19</td>
<td>29</td>
<td>21</td>
</tr>
<tr>
<td>% increase 94</td>
<td>102</td>
<td>78</td>
<td>43</td>
<td>28</td>
<td>164</td>
</tr>
</tbody>
</table>

Note: site tree density 16 trees ha\(^{-1}\); each tree canopy covering 100 - 150 m\(^2\). Although the site had been protected from cattle for a number of years, it is not clear whether it had been cultivated on a millet/peanut rotation or not (Dancette et al. 1969).

Table 5.2. Estimated annual nutrient return from Acacia albida leaf fall (kg ha\(^{-1}\) A. albida canopy area) (From Charreau et al. 1965).

<table>
<thead>
<tr>
<th>N</th>
<th>Ca</th>
<th>Kg</th>
<th>K</th>
<th>P</th>
<th>S</th>
</tr>
</thead>
<tbody>
<tr>
<td>75</td>
<td>131</td>
<td>24</td>
<td>16</td>
<td>12</td>
<td>20</td>
</tr>
</tbody>
</table>
Table 5.3.  A) Annual return (Kg) of nutrients to the soil by different parts of an *Acacia albida* tree (Bambey - Senegal); B) annual return (Kg) per ha for 3 tree densities and cropping regimes (details below table) (From Charreau *et al.*, based on Jung 1966).

<table>
<thead>
<tr>
<th></th>
<th>Dry matter</th>
<th>N</th>
<th>P</th>
<th>K</th>
<th>Ca</th>
<th>Mg</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>A leaves</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>wood + bark</td>
<td>45.5</td>
<td>0.58</td>
<td>0.01</td>
<td>0.12</td>
<td>2.33</td>
<td>0.23</td>
</tr>
<tr>
<td>fruit</td>
<td>124.7</td>
<td>1.66</td>
<td>0.05</td>
<td>1.23</td>
<td>0.52</td>
<td>0.15</td>
</tr>
<tr>
<td>total</td>
<td>267.5</td>
<td>4.30</td>
<td>0.09</td>
<td>1.74</td>
<td>5.14</td>
<td>0.96</td>
</tr>
<tr>
<td><strong>B Maximum</strong></td>
<td>11583</td>
<td>186.5</td>
<td>3.9</td>
<td>76.1</td>
<td>222.1</td>
<td>41.9</td>
</tr>
<tr>
<td><strong>Medium</strong></td>
<td>5350</td>
<td>69.4</td>
<td>1.7</td>
<td>32.3</td>
<td>79.7</td>
<td>68.9</td>
</tr>
<tr>
<td><strong>Minimum</strong></td>
<td>1428</td>
<td>26.4</td>
<td>0.3</td>
<td>5.1</td>
<td>46.2</td>
<td>8.1</td>
</tr>
</tbody>
</table>

**Note:** 3 assumptions are made for the estimated nutrient return per ha:

**Maximum:** dense *Acacia albida* stand (44 trees ha⁻¹) with a continuous canopy cover; return to the soil of all organic products;

**Medium:** 20 trees ha⁻¹ stand, with a 0.46 ha canopy cover; consumption of the pods by livestock with a 50% return for N and 90% for mineral nutrients.

**Minimum:** 10 trees ha⁻¹ stand, with a 0.23 ha canopy cover; export of all pods.
legumes should be improved due to the lower temperatures and the longer periods of moisture availability at greater depths. Felker (1979) calculated (based on the likely N input by rain and blue green algal lichen crusts in desert systems, and protein production and removal levels) that Prosopis tamarugo in Chile is likely to fix c. 200 kg N ha\(^{-1}\) year\(^{-1}\) (assuming the pod and leaf yields of 12000 kg ha\(^{-1}\) yr\(^{-1}\) average 10% protein at 1.6% N to be correct and to be removed from the system by sheep).

The influence of the pasture layer on the nutrient regime of trees.

In the early stages of tree growth, ground vegetation close to saplings may compete considerably with trees for nutrients. In the S.W. U.S.A., the herbaceous layer (and litter decaying fungi) often deprive Ponderosa pine seedlings particularly of nitrogen and phosphorus which are deficient on many soils (Schubert 1974). Similar results are often found (e.g. Squire 1977 for Pinus radiata D. Don on a heavy soil in N.E. Victoria, Australia). The deprivation of nutrients to trees which may have their roots below the grass rooting zone may also occur when the accumulation of nutrients takes place in the herb layer and either their release to lower layers is slow or a very tight external cycling occurs in the herb layer – i.e. the sum of the pool of internally cycled nutrients (in the tree) and the mineralization and exchange capacity in the lower soil depths is insufficient for the tree. The accumulation and slow breakdown can be due to low pH, low temperatures, high C/N, C/P, C/Ca ratios (Heal 1979) in cooler climates, and to hot dry conditions is more arid and tropical climates (e.g. Ball et al. 1981 in Pinus elliottii plantations in N. Florida; Thiault 1981 for several tree species in some dry mediterranean forests in France).
The timing of the demand by the various components of a
tree pasture intercrop may be in part complementary or may
overlap and be detrimental. In France in apple orchards which
have a grass cover crop, the high nitrogen demand by the grasses
in the spring and after each cut seems to create a shortage
of nitrogen for the apple trees at those specific times (Baldy
1971); the time of maximum demand for nitrogen by trees varies,
and therefore one should attempt to match the release of $N$ from
cut grass and the lowest demands for $N$ by the grass with that of
demand by the trees. The timing of $N$ demand also varies between
different grass species. On the other hand, the grass cover
crop seems to have a positive effect compared to cleared sites
concerning the distribution of added $P$ to the trees.

The use of nitrogen fixing herbs or shrub/trees is beneficial
in some environments to the associated non-nitrogen fixing tree
crop. In northern Alabama, a young Sycamore (Pseudoplatanus
occidentalis) plantation had a volume, 4 years after planting,
of $52 \text{ m}^3 \text{ ha}^{-1}$ with a Trifolium spp. cover crop, while without
clover, the volume was $14 \text{ m}^3 \text{ ha}^{-1}$ (Kormanik 1979). On a well
drained silt loam in Indiana, Clark et al. (1979) found 10 years
after planting that Black walnut (Juglans nigra L.) grown in
mixture with Autumn olive (Eleagnus umbellata Thumb) was
significantly taller (by c. 1 m) and thicker stemmed (c. 1 cm)
than those interplanted with Robinia pseudoacacia, and 2.5 m
taller and 2.5 cm thicker stemmed than a control plot which was
not interplanted. Other examples of the likely benefit of legumes
to trees are mentioned by Kinnel et al. (1979) for Pinus
radiata in S.W. Australia, Plucknett et al. (1972) for
Stylosanthes guianensis in Eucalyptus saligna stands in Hawaii
and Leucaena leucocephala for teak (Tectona grandis) plantations in Java.

5.2.3 Genetic selection and nutrient relationships.

The selection of the correct species in tree pasture systems for maximum complementarity and least nutrient competition is vital.

Steel et al. (1974) on sandy sites in Bali with a legume understorey to coconut, found that the relative capacity to extract P (per unit root weight) varied between 3 legume species and was highest in Lotonis bainesii c.v. Miles. However the utilization of P in growth was most efficient in Centrosema pubescens (centro) as was the use of P in improving the N yield and therefore presumably also in improving nitrogen fixation.

Further the correct choice of genotypes is likely to make significant differences as far as nutrient relations are concerned. Blackman et al. (1979) found on a site near Stoneville (Mississippi) that clones of Populus deltoides Bartr. of Louisiana, Mississippi and Southern Illinois origin showed differential yield response (efficiency of biomass production from available nutrients). Louisiana clone produced a significantly greater ($P < 0.05$) amount (640 g) of dry matter per gram of N than the Southern Illinois clone (430 g) and Mississippi clone (540 g). Significant differences in total dry matter production per gram of K also occurred while differences in total production dry weight per unit amount of P, Ca and Mg were not significant; however for some of them there was a significant difference when comparing different parts of trees: this would become important when harvesting
strategies are involved. For instance Louisiana trees had significantly more Ca in current year branches than other clones.

In replicated pot experiments, Felker et al. (1980) found that nitrogen fixation levels (acetylene reduction) by 13 Prosopis accessions varied significantly between species; a Hawaiian Prosopis pallida fixing 10 times more nitrogen than P. glandulosa var glandulosa from Texas. Tree varieties or clones which perform well at high stocking densities may not be the ones which can maximize production at reduced stocking densities (e.g. Sonduelle 1980, on poplar).

5.2.4 Conclusion.

The above review on nutrient interactions between tree, shrub and pasture plants only points to the kind of information which is required if one is to develop species mixes and management strategies of those mixes which are to optimise the long term production potential of a site from a nutrient point of view. Not only is one dubious about drawing conclusions from much of the evidence on the influence of trees or pasture plants on each other's nutrient relations because of poor sampling and experimental procedures, but in most cases, the evidence only points to the results of a specific situation at one point in time and sometimes for only a small part (e.g. top 10 cm of soil) of the whole volume of material which is involved in nutrient cycling. Few investigations manage to convincingly explain the nature of the nutrient interactions, the rates of cycling of different nutrients and their location in the soil–plant–atmosphere system at different times (for a thorough discussion of some of these problems see Stone 1975).
Hence it is seldom possible to make predictions on the impact which specific levels of nutrient offtake from the site may have on the nutrient status of the soil at different depths and therefore on subsequent site productivity potential. Neither is it possible to assume that the outcome of a specific species mix on one site is likely to be the same on another site where the nutrient status of successive soil depths is different and/or if the root distribution of the various species is different.

It would seem that there is a potential for combinations of tree and pasture plants to optimize production for man's use from a given amount of nutrient input each year into the system; however we have a long way to go before the complementarity of different species, varieties and clonal mixes can be worked out. Further, selection for varieties or clones appropriate for specific mixes on specific sites could make all the difference between a certain degree of complementarity and negative interactions, between the components of a species mix, from a nutrient point of view.
5.2 Allelopathy.

Allelopathy usually refers to any direct or indirect harmful
effects of one plant on another by the release of chemical substances
(allelochemics) into the environment (Spurr and Barnes 1980);
however allelochemics will here refer to chemicals from one plant
which influence another directly or indirectly (e.g. through
microorganisms) without specifying the nature of the effect; as
Tukey (1970) suggested it allows for both stimulatory and
inhibitory substances to be released from plants.

Chemical constituents potentially involved in allelopathy
are released from plants in four different ways (Tukey 1970,
Rovira 1969, Whittaker and Feeny 1971):
- abscission of leaves and other plant parts (litter fall);
- volatilization of substances;
- root exudation;
- leaching from above ground parts.

Litter-fall (leaves, bark, dead roots) returns the greatest
quantities of substances to the soil; accumulated residues may
exert an influence throughout the year, either directly or
indirectly as biproducts of microbiological breakdown.

Volatile substances such as ethylene and terpenes are released
from leaves; root exudates are varied and include sugars, amino
acids, peptides, enzymes, vitamins, organic acids, fungal stimulants
and inhibitors.

Leaching from leaves and other aerial parts may include many
of the above as well as all the essential inorganic nutrients,
growth regulating chemicals such gibberellins, and alkaloids.

Under laboratory conditions it can be easy to demonstrate that
Allelochemicals from a wide range of plants can have a significant influence on germination and growth of various plant species; however, under natural field conditions, it is more difficult to be certain as to the relative contribution of allelochemicals to plant interactions in specific situations. Nevertheless, a growing amount of information is available on the allelopathic effects of grasses and forbs on each other, on trees and vice versa.

5.3.1 Evidence from tree-herb interactions:

In the widespread pine (Pinus ponderosa) and bunchgrass community (Festuca arizonica and Muhlenbergia montana) of Northern Arizona, the lack of success in recolonization by pine for up to a hundred years subsequent to clearing by fire and logging, is likely to be due in part to grass phytotoxins (Rietveld 1975). Phytotoxins were present in extracts prepared from live green foliage of both grass species and from fescue new litter which significantly reduced certain parameters of pine seed germination and seedling radicle growth. Fescue foliage extracts for instance reduced significantly (at 1% level) compared to the control, mean pine seed germination by nearly 50%, speed of germination by 50%, radicle length by about 30% and mean speed of radicle elongation by about 30%. The amount of residues used to prepare the extracts were conservative compared to the amounts that occur in nature (but the amounts and timing of the release of the compound(s) may not be similar in nature). While the grasses are known to be superior competitors to young pine for available water and nutrients and for growing space, it is likely to be the combined effect of competition and an allelopathic mechanism which have prevented
new pine seedlings from becoming established.

Brown (1967) noted that Jack pine (Pinus banksiana Lamb) forests in Northern Michigan have an extremely uneven distribution of trees ranging from a few individuals per ha to 2000 or more per ha within short distances. 56 different plant species were screened for the effect of their water leachates on Jack pine germination. The extracts from some species were found to be very inhibiting (e.g. 2 Prunus species), some had little or no effect and five were found to have stimulated germination in some experiments. Cornus canadensis for example, was subsequently found to contain both germination stimulators and inhibitors, the inhibitor losing its effect in the soil quicker than the stimulator.

However, in experiments with Jack pine, there was no close agreement in the relative allelopathic effects on pine seed germination and seedling growth between tests in the field under pure stands of the different species and greenhouse germination tests with the same species. Nevertheless, it is the subsequent growth of the seedling which is of crucial importance to the reproductive success of Jack pine; this will depend on other factors (light intensity, moisture level, degree of fungus attack, e.g. "damping off", mouse damage, needle accumulation etc.) which are affected in yet different ways by the species associated with the Jack pine. Although in association with Cornus canadensis and Pinus resinosa germination of Jack pine seeds was very good, the poor survival of seedlings was due to increased incidence of damping off - in the case of the former, and smothering by needles - in the case of the latter.

Jarvis (1964) found that Deschampsia flexuosa (L) Trim.
humus contained a water soluble, heat stable substance which was inhibitory to root growth of sessile oak (*Quercus petraea*) and birch (*Betula verrucosa*) at the seedling stage. Experiments showed that birch seedling growth was reduced when in association with *Deschampsia*; although in the field a further reason may have been due to the higher competitive ability of *Deschampsia* for nutrient uptake, a contributary factor seemed to be the likely leaching of a phytotoxin from the roots of *Deschampsia*.

Among the early (nineteen thirties) investigations of allelopathy were those in its commercial implications in rubber and coffee plantations in the Far East (*Audus 1972*). In the early stages of plantations, before canopy closure, the need for cover crops to reduce soil erosion and soil structure degradation is desirable. However it was found that many cover crops had a deleterious effect on young tree growth through the release of toxic root exudates rather than through competition for nutrients; the worst offenders in coffee plantations were *Salvia occidentalis*, *Paspalum conjugatum*, *Cynodon dactylon*, *Passiflora faetida* and *Amaranthus spinosus*.

Investigating the mechanism by which heather (*Calluna vulgaris*) inhibits birch (*Betula pendula*) and Spruce (*Picea abies*) from forming mycorrhizal associations and keeps them in check for many years, *Robinson (1973)* found that either the *Calluna* root or its endophyte produced a fungitoxin (at 15°C) to which several fungi (e.g. the specialized mycorrhiza fungus *Amanita muscaria*) were susceptible (at 20°C). In the absence of grazing pressure, birch can colonize heather heaths; through ageing not only are gaps created in a heath community but the production of the fungitoxin is reduced.

*Horsley (1977)* investigated the reason for which small black cherry (*Pinus serotina Enrh.*) seedlings grow slowly and soon die
in low density cherry and maple (Acer rubrum L.) orchard stands which are colonized by a dense ground cover of bracken fern (Pteridium aquilinum L.), wild oat grass (Danthonia compressa Aust.), golden rod (Solidago rugosa Ait.) and flat topped aster (Aster umbellatus Mill.). Aster foliage and golden rod and aster root washings substantially inhibited cherry shoot growth subsequent to cotyledon exhaustion though germination and initial growth were also inhibited. Phenolic compounds were thought to be responsible. Under field conditions, growth and germination of cherry seedlings nears normality only 2 years after removal of the herbs. The slow breakdown of toxins in the soil is thought to be due to a low pH (3.9) and to impeded drainage.

In Ontario, Fisher et al. (1978) looked at the germination of sugar maple (Acer saccharum Marsh.) and the growth of 2 + 0 seedlings in old fields and weeded plots compared to plots in forest soil. The leachates of Aster and Solidago fresh leaves reduced both maple germination and growth (radicle extension); leachates from leaves of Ambrosia spp., Erigeron spp., and Hapacium spp. which had been allowed to putrefy for 30 days significantly inhibited maple germination (but not growth), suggesting that for some species it is either the decay process itself or the microbial activity associated with it which releases allelo-chemics.

Testing the response of 2 + 0 potted maple seedlings with leachate of either Aster nova anglica or Solidago canadensis mulch, living roots or leaves, it was found that it was the leachates of mulches which significantly reduced seedling growth. Phosphorus, calcium and magnesium content in the seedling was reduced while potassium increased. As the seedlings were given
excess nutrient input, it was thought that the reduction in growth was not due to competition for nutrients by the microflora but to allelochemics. In a further experiment, the interaction of N and P at different concentrations and of the allelochemical activity of Solidago mulch were investigated on potted plants for 6 months. The dry weight and NPK content of the seedlings were then measured. In the absence of N and P the dry weight was significantly lower with mulch than without. The P addition alleviated the negative effect of the mulch more than the N addition; some treatments did not reduce N content but did reduce growth, P and K contents. But there was an N and P interaction whereby 100 ppm P and 200 ppm N combined were effective in swamping the Solidago allelopathic effect.

In this situation, it seems that the putrefaction process increased the inhibitory activity of Aster and Solidago foliage and enabled the extraction of inhibitory compounds from another 3 species. Either the microorganisms produced the allelochemicals from plant compounds or the allelochemics were released more easily from the plant after putrefaction. The interference may have been due to reduced root growth and therefore to a reduced ability to absorb nutrients. However as this reduced ability varied for different nutrients, there was interference with the selectivity of nutrient uptake and especially P. The soil system may deactivate the allelochemicals over time, a process which they suggested may be dependent, on nutrients, especially phosphorus.

In Central America, Marinero Moreno (1962) suggested that the greatly reduced growth of Cordia alliodora (R & P) Cham. seedlings when associated with the grass Melinis minutiflora
Beauv. was likely to be due at least partly to toxins produced both in the grass roots and leaves.

Some grasses are thought, through the secretion of toxins to inhibit nitrification in Zimbabwean grasslands (Audus 1972) and in West African Savana such an inhibition reduces the growth of Eucalypts (Dommergues et al. 1979).

However although Moore (1975) acknowledged the possibility that some grasses of the African savanna may produce allelochemicals which inhibit nitrification, he reported on the suggestions for other mechanisms which may be involved in the case of *Hyparrhenia* spp. grassland: high acidity, the immobilisation of ammonium ions by root tissue thereby removing a substrate from nitrifiers, or when high concentrations of amonium are present, the low phosphate levels to which nitrite oxidisers are particularly sensitive.

The likely allelopathic effect of certain tree species on other plants has long been recognized. Black walnut (*Juglans nigra*) releases an allelochemic from its leaves, roots and hulls. While alfalfa and tomato plants are killed up to 2 to 3 times the radius of the tree canopy, other species such as maize and beets are not affected and yet others such as Kentucky blue grass (*Poa pratensis L*), *Phleum pratense L* and *Rubus occidentalis L* become more abundant than usual under walnut trees (Brooks 1951, Krebs 1972).

Madwick and Ovington (1959) found in S.E. England that the average contents of sodium, potassium, calcium and magnesium in precipitation in the open were 19, 3, 11 and less than 1 kg/ha/annum respectively while under the forest canopy it was 33, 24, 24 and 10 kg/ha/annum. The deciduous trees leached more nutrients while in leaf than coniferous species, and the reverse was true.
during the winter. However there was still a wide variation, both in the relative amounts of different nutrient leached at different times of year, and between species as to the average amount of nutrients leached per year; for instance the potassium content of rain per year over a two year period was 2.8 kg per ha for open plots, 24.2 kg as an average for forest plantations, 12.3 kg for Quercus rubra, 39.0 kg for Larix eurolepis and 58.4 kg for a hardwood coppice.

In the 1880's in Germany two researchers observed much improved growth of plants beneath the spread of beech (Fagus sp) maple (Acer sp), lime (Tilia sp) trees as compared with poplar (Populus sp) birch (Betula sp) and willow (Salix sp) (Tukey 1970). They felt that the improvement in growth might be due to nutrients leached from the overhead canopy.

Baker (1978) reported on a study in the Coast Ranges and Sierra Nevada (U.S.) which determined that under natural conditions the faster and taller growth of certain grass species (e.g. Bromus rigidus) under blue oak (Quercus douglasii Hook and Am.) compared to away from canopy influences was due in part to litter and leached material from the blue oak itself.

In coastal California, the growth and reproduction of many annual herb species, both native and introduced, are severely restricted by interference due to Eucalyptus camaldulensis Dehn. on fine sandy loams (Del Moral and Muller 1970). It was found not to be an effect of competition for nutrients, light or moisture though the pattern of inhibition was partially correlated with levels of soil moisture. Three fairly distinct zones occur: the litter zone under the Eucalypts, with no herb layer; a bare
zone 2 - 5 m broad from the edge of the Eucalypts stand edge where few herbs occur except on the northern side of the stand where moisture conditions are higher and the litter zone merges directly with the third grassland zone. Early in the growing season (after the first rains in November) and when the soil moisture regime could not be limiting in any of the zones, the density of plants in the litter zone was already only 0.15% of that in the grassland and their height averaged 57% of those in the grassland. Some other factors inhibitory to early season growth was at play. Terpenes were found to be adsorbed to soil particles under Eucalyptus camaldulensis and decreased in concentration away from the stand. Their concentration was high between November and February at the time of germination and growth of annuals, but by the end of the growing season had dropped to low levels. It was only the leaves which were found to produce and volatize these terpenes which diffuse and settle on the soil where they are adsorbed. The dryness of the soil at this time facilitates adsorption and probably suppresses their microbial degradation. Hence toxicity is highest when seeds begin to germinate. Of the terpenes identified and tested for their toxicity in bio-assay tests with 5 grasses found commonly around the Eucalypt stands, cineole was found to extremely toxic, followed by pinene and phellandrene (cineole apparently inhibits mitochondrial respiration and cell division). At different toxin concentrations the ranking order of sensitivity (measured in terms of reduced radicle growth) of the different grass species changed.

Experimentally, Bromus rigidus seedlings in atmospheric contact with macerated Eucalypt leaves were found to have significantly (at 1% level) reduced radicle growth by an average of
31% compared with controls. Further Bromus radicle growth in a loam previously in atmospheric contact for 3 hours with macerated Eucalypt leaves was found to have been reduced significantly by 21%.

Prior to the first rains leaf litter also possesses significant quantities of leachable, water soluble potential toxins. Subsequent to rainfall a dramatic decrease in the potential toxicity of the leaf litter occurs. The height growth and dry weight increase in several annual herbs were significantly reduced by leachates from leaf litter in a controlled experiment where no competition from Eucalypt roots took place. Ten compounds leached from the litter were found to be toxic (5 phenolic acids, gallic acid, ferulic acid, coumaric acid, chlorogenic acid and caffeic acid) to Bromus rigidus growth. But in a controlled experiment, soils taken from different depths (in the top 6 cm of soil) from under a Eucalypt stand immediately after the onset of rains showed increasing toxicity at lower depths indicating a concentration of toxins. However these toxins were different to those identified from the leaves; the latter may therefore have been polymerized to other toxin compounds. As concentrations of the toxins are altered, the ranking of their relative toxicity also changes. But for each of 6 bio-assay species tested the response curves for all phenolic acids were similar which suggested to Del Moral and Muller that the toxins are acting on the same enzyme complex. It seems that the sensitivity of the species tested decreases with increasing seed weight (apart from Eucalypt which is least affected by its own toxins).

From observations during unusually wet and dry years and from experiments in the litter zone, with trenched plots to reduce
competition for water by Eucalypt roots, it seems that abundant soil moisture compensates partially for the effects of the toxins whereas scanty soil moisture enhances the effect. Soil type also influenced the toxicity of the allelochemics, since on sandy well drained soils little difference occurred between the grass vegetation in the grassland and the litter zone. An experiment tested the effects of soil differences by loading a sandy soil and a loamy soil with terpenes. No difference was found in germination success and radicle growth of Bromus between untreated soils and treated sandy soils, but there was a statistically significant 26% reduction in growth in the treated loam compared to the control loam.

Similarly Eucalypt litter was leached on two different soils to test for differences in the effect of phenolic toxins. Radicle growth on treated sand was reduced by 22% compared to the control, while a 58% reduction occurred in the loam. To test this result further, columns of sand from beneath Eucalypt were exchanged for columns of loam from under Eucalypt with as little disturbance as possible and covered with leaf litter. Again the inhibition of growth was statistically more severe in loam.

It seems therefore that sandy soils do not concentrate significant levels of toxins since they lack sufficient colloidal material. Heavier soils however concentrate toxins near the surface by poorer infiltration of water bearing the toxins, and by direct adsorption of terpenes to colloidal particles. Further on soils where drainage is impeded, the denaturization of toxin is much lower than in well drained soils.

Hence several factors combine to reduce the annual herbaceous grassland flora from Eucalyptus camaldulensis groves. Their
effects vary gradationally and temporally within the ecosystem and may act to enhance or reduce the effect of the toxins.

Substantial further evidence exists for attributing changes in the ground cover composition or biomass under the canopy of trees primarily to allelopathy rather than to light, moisture or nutrient conditions. De Bell (1971) identified the leaching of salicylic acid from cherry bark oak (Quercus falcata Var. pagod-oefolia EIL.) in Coastal South Carolina as the main reason for retarded vegetation under their canopy compared to other trees. Del Moral and Cates (1971) screened 40 species in Western Washington for the production of inhibitory volatile and water soluble compounds from bark, leaves, roots and litter. High inhibition values in the laboratory were often associated with distinct changes in ground cover composition beneath the canopy of the species concerned.

In New Zealand, Lill et al. (1975) found a site of 39 year old Pinus radiata (density 300 sph) the understorey of which should have been suitable for white clover and ryegrass germination and growth; soil moisture conditions were not limiting. They assayed for clover and ryegrass germination and clover hypocotyl and ryegrass plumule growth rates in incubated jars which contained volatiles from radiata pine litter. Seedling growth was significantly ($P < 0.05$) reduced from 25% to over 50%; germination was increased in clover (by less than 10%) but reduced significantly by 25% to more than 50% for ryegrass.

Lodhi (1976) found in Missouri that relatively low herb productivity under Sycomore (Plantanus occidentalis), hackberry (Celtis occidentalis), red oak (Quercus borealis) and white oak (Quercus alba) compared to that under elm (Ulmus americana)
appeared to be due at least in part to the production of toxins from decaying leaves and leaf leachates; though tree influences on pH, nitrification and mineralization rates by developing variable physico-ecological niches may also have played a role (Lodhi 1977). Nitrifiers (Nitrosomonas and Nitrobacter) numbers and nitrate nitrogen levels were lower under trees than away from trees (but ammonium nitrogen higher) and the inhibitors to nitrifiers and nitrification are likely to be from leaf leachates or toxins released from leaf litter (Lodhi 1978).

Lodhi and Killingbeck (1980) in a Ponderosa pine (Pinus ponderosa Dougl.) stand in North Dakota where the pH is between 7.25 and 7.75 have attributed the low nitrate nitrogen relative to ammonium nitrogen and low numbers of Nitrosomonas and Nitrobacter in the soils to the production and subsequent transfer to the soil of secondary plant chemicals. These toxins were found in extracts from pine needles, bark and A horizon soils. The extracts were toxic to suspensions of Nitrosomonas in nutrient solutions causing significant reductions in numbers from 68% to 93% of the control. They rejected the possibility that low nitrification levels were due to perennially low NH$_4$ - N levels due to rapid vascular plant uptake thereby leaving insufficient NH$_4$ - N for nitrifier populations since soil microbes are usually more efficient at absorbing soil nitrogen than vascular plants.

Rice (1977) reported a similar situation of nitrifier inhibition in one grassland climax and two forest climax communities in Oklahoma. In the early stages of old field succession however N$_2$ fixation was found to be slowed by toxins released from early colonizers.
5.3.2 Other relevant evidence and discussion.

It seems clear that plants can have either a positive or a negative effect on each other through the release of chemicals into the environment. There are however great difficulties in determining the relative contribution of such chemicals to the range of mechanisms of interaction occurring between plants under field conditions. Experimentation is made particularly difficult when the soil is the site of production of the allelochemics and/or the medium through which they are allegedly influenced, since any disturbance of soil chemistry and structure can significantly influence the production and the processing of the allelochemics as well as the mechanism by which the receiver plant is sensitive.

It is not justifiable to generalise about the type and extent of an allelopathic interaction between individuals of 2 (or more) species or even between individuals of the same species, based on observations on the results of experimentation in only one specific situation. Many environmental factors as well as factors specific to the interacting individuals alter the allelopathic interaction.

The age of the producer affects the quality and quantity of substances released (for example the reported case of heather inhibitors on Norway spruce mycorrhizal fungus). Tazaki and Nichols (1978) found that bark from 15 years old Pinus radiata was less toxic than from 35 year old trees to the growth of turnip, lettuce and tomato seedlings. The elimination of toxicity by ageing and composting took 35 - 40 days for 15 year old tree bark while bark toxicity from 35 year old trees still remained after 90 days. Mature tissue (especially leaves) approaching senescence is very susceptible to leaching of organic and inorganic compounds compared to young tissue (Tukey 1970, Madgwick and
Ovington 1959). More gibberellins are leached from flowering sweet corn \((\text{Zea mais})\) plants than from non flowering plants (Tukey 1970).

The healthiness of a plant, for instance its nutrient status, has also been found to be important. A high level of exudation of organic compounds from roots was found in phosphorus deficient \(\text{Pinus radiata}\) (Rovira 1969). Lehman and Rice (1972 - quoted in Newman and Rovira 1975) found that nutrient deficiency increased the amount of a toxin, chlorogenic acid, in sunflower \((\text{Helianthus annuus})\) tissues.

When plants are injured, either mechanically, by microorganisms, insects or other pests, certain toxic substances are sometimes produced both in the roots and leaves and these may be leached out or be exuded (Tukey 1970, Rovira 1969). Other environmental factors such as soil moisture, light, temperature and the medium supporting the roots have been found to affect root exudations (Rovira 1969) in certain species, while temperature and light affect leaching from plant leaves (Tukey 1970). The intensity and volume of rain affect the efficiency of leaching; rain falling as light drizzle removes considerably more nutrients from leaves than does a greater quantity of water falling over a short period.

In some instances it is the leaf substances, subsequently processed by animals which act as strong toxins: the frass of chrysomelid insects feeding on \(\text{Eucalyptus globulus}\) leaves reduce the germination of mustard seeds \((\text{Brassica sp})\) to less than one tenth of that of controls (Trenbath 1976).

If the allelochemics act through the medium of the soil, the soil characteristics will influence the extent to which some of the chemicals are absorbed on its particles and are thereby either concentrated in specific soil zones or leached out. The
soil characteristics (degree of aeration, pH, nutrient availability) also affect microbial activity which may influence the rate of processing of the released compounds to either more or less toxic/beneficial compounds (e.g., the situation with Eucalyptus camaldulensis mentioned above by Del Moral and Muller). Dommergues, et al. (1979) reported that the compounds produced by sorghum (Sorghum vulgare), which are toxic to subsequent sorghum crops remain in the soil as long as environmental conditions prevent their biodegradation by soil microorganisms; in Central Senegal this was the case in sandy soils containing kaolinite type clays but was absent in vertisols containing montmorillonite type clays.

The qualitative and quantitative influences of allelopathy also depend on the sensitivity of the receiver plant. This is influenced, as for the production of the compounds, by a whole range of environmental factors as well as by the characteristics of the plant such as its age, physiological status, etc., at the time of the presence of allelo-chemics in its immediate environment. For a plant may respond differently to given amounts of certain allelo-chemics at different developmental stages. Gibberellins at one concentration may be stimulatory to stem elongation and inhibitory to flowering at another concentration (Tukey 1970).

Some of the disagreements between authors concerning the relative role of allelopathy in plant to plant interactions are likely to be due to environmentally and genetically induced variation both in the rates and timing of production of the allelo-chemics and in the susceptibility of the "receiver" plant. Allelopathic effects also act in combination with other interactions (moisture, climate, nutrients) which occur between trees and
associated vegetation. The sometimes conflicting reports concerning the affects of *Eucalyptus camaldulensis*, *Eucalyptus globulus* and other *Eucalyptus* on associated herbs (and vice versa) are an example of this (Tejwani 1979, Del Moral and Muller 1970, Story 1967). Tejwani's discussion disclosed negative effects of *E. globulus* in Kenya's arid and semi-arid zones on vegetative undergrowth, while in India considerable quantities of fibre grass (*Eulaliopsis binata*) of reasonable quality were obtained under *Eucalyptus* spp. in an area with 1100 mm rainfall. Story in Australia referred to different areas with varying environmental conditions where grass production in association with *Eucalypt* species can be as low as \( \frac{1}{3} \) of that in neighbouring grassland with no trees, and other areas where *Eucalyptus camaldulensis* has such a beneficial effect on the grass that yields are all but doubled by the trees' influences.

In conclusion it seems clear that allelopathy occurs (though it is very hard to prove conclusively), that it may be a contributory cause of observed interactions which are sometimes attributed to other causes such as competition for moisture or nutrients.

The implications of allelopathy for the design of intimate mixtures of trees with either pastures or crops are that some species or varieties may be unsuitable as intercrop components under specific environmental conditions. However this may not be the case for different combinations of species involving the allelopathic producer or even the same mixture but under different environmental conditions. Species which inhibit \( \text{N}_2 \) fixation should probably be avoided and replaced, while care should be taken not to mix species which inhibit nitrification with species which rely primarily on nitrate for their nitrogen requirements;
certain species are known to have preferences for either NH$_4$ - N or NO$_3$ - N at least under specific soil conditions (e.g. pH) (Bigg and Daniel 1978, Gigon and Rorison 1972). In environments where frequent rains leach a significant proportion of nutrient from leaves in tree canopies, and where the soil nutrient retention capacities are not high, an understorey of a suitable plant able to absorb part of the nutrients through the leaves (e.g. pine, maple) would be desirable.
5.4 Erosion.

As indicated in chapter 4, the leaves of certain trees can concentrate the raindrops into drops of larger size. Ohler (1969) commented on the disadvantage in some situations of keeping a clear soil surface underneath coconuts because of the erosion which occurs. In the highlands of North Thailand, grasslands (mainly *Imperata cylindrica*) produce more run off than established forest plantations, but more sheet erosion occurs under forest than in grassland because the considerable areas of bare soil under the trees are unable to absorb the energy of the raindrops from the tree leaves (Falvey et al. 1978).

Scattered trees may be so detrimental to pasture production that exposed inter tree areas are more liable to wind and or water erosion than if trees were absent and a better grass cover was able to develop. Such a situation is said to occur with *Prosopis juliflora* in the S.W. U.S.A. (Tiedemann et al. 1973). However overgrazing may be a contributory factor; the carrying capacity of rangeland amongst scattered mesquite is likely to vary considerably from year to year (section 5.1.2) and if the livestock density is not carefully adjusted each year to that carrying capacity, overgrazing and consequent soil exposure to wind erosion must ensue.

Story (1969) found that in areas of New South Wales where scattered trees (several species) considerably reduced pasture production and ground cover, the trees encouraged run off and soil erosion by rain.

It seems therefore that in certain situations, e.g. Northern Thailand, a grassland tree mixture may provide the best protection
against erosion on the site as well as least run off from the area which may be of importance to erosion below the site, while in other situations (climatic, species mix) erosion rates may be reduced by not having trees in pastures.

5.5 Conclusion.

The soil mediated relationships between trees and pasture plants are specific to site and time for a whole range of factors; further, they are species specific and evidence suggests that considerable ecotypic specificity may also occur. It is therefore very difficult to predict from knowledge of one site with any degree of precision what the outcome of such relationships may be on other sites which may vary even only slightly in some of their characteristics. The relationship may be negative or positive for many factors, or may be positive for some - e.g. nutrients, and negative for another - e.g. moisture; in the latter situation, a sequential integration on the same site may avoid the negative interaction while still taking advantage of the positive interaction.
PART II

INTEGRATED AGRICULTURAL, PASTORAL AND FORESTRY SYSTEMS

In part I the theoretical basis of physical interactions between trees and pasture, and between trees and livestock was examined and analysed. It is now necessary to look at some of the ways in which tree and animal production can be integrated. Integration can take several forms and five broad categories can be distinguished on the basis of the objectives:

i) the trees or forest confer indirect benefits on animal production;

ii) livestock are used to benefit forest production;

iii) forest, forage and animal production objectives are met concurrently from the same site;

iv) trees are grown to produce fodder thus confering direct benefit on animal production;

v) financial benefits are derived from concurrent forest and animal production within the same management unit even though there are no extra benefits in terms of physical production.

There can, of course, be a considerable overlap between these five categories. The main aim with the first four categories is to create synergy in that by careful association of tree production, forage production and animal husbandry, the sum of benefits in terms of tree, pasture and animal products is greater than that from any production system in isolation. The emphasis is in terms of biological rather than economic production.

In Chapter 6, some of the indirect benefits which forestry may
confer on animal production are discussed and a number of management practices are described which may reduce the harmful interactions and enhance the beneficial interactions. This chapter sites a number of different examples because this aspect of the animal-pasture-forestry complex is one which is seldom touched upon in the current agroforestry literature.

Chapters 7 to 9 discuss the role of agro-silvopastoralism in the context of farming systems of Western Rajasthan. Although a discussion of the various forms of silvopastoral systems could have been tackled on the basis of the five main objectives outlined above for different ecological and socio-economic situations, it was felt that a thorough analysis of the research results of the role and potential role of agro-silvopastoralism in one particular area would be more worthwhile. Western Rajasthan is particularly suitable since some research on various aspects of the subject has been carried out for more than 20 years and reported benefits of agro-silvopastoral integration could be of substantial assistance in the introduction of such systems to other parts of the world. Unfortunately, the results of this research is at times contradictory and no overall evaluation of the actual integrated system or of its further potential appears to have been made.

Any attempt to compare production in financial terms is likely to be frustrated by large differences that exist in costs between countries and regions and in the costs of various alternative management inputs relative to financial returns. Financial comparisons are also made more difficult by differences in the way financial costs and returns are shared between society and the individual farm unit and even in the way these units and their respective societies evaluate
costs and benefits. Consequently, the emphasis is on benefits in terms of physical production. Nevertheless, examples are given of the costs and returns of some integrated production units to show how these may influence the relative merits of integrated versus non-integrated production, and the desirable or optimum composition of integrated production.
The Indirect Role of Trees in Livestock Production

Trees may exert a considerable influence on animal production and/or management in three broad ways:

i) their influence on the animal's microclimate may affect production directly through modification of its temperature regime and indirectly through changes in water demand, in spacial and tempereal grazing pressure and in animal health;

ii) by acting as physical barriers to stock movement between grazing units;

iii) by affecting the associated ground vegetation (this point is discussed in Chapter 2).

The trees may have no other function than that of improving livestock production or management; in such a situation the trees can be managed so as to maximize their beneficial influence on livestock and the costs of tree establishment and maintenance should be less than the expected increased benefits in terms of the livestock production values discounted back to some appropriate point in time.

If the trees can be expected to have a value of their own, the greatest benefits are obtained by managing the livestock and the trees in such a way that the extra benefits derived by the livestock through their association with trees are devised while imposing least cost and to impose minimal loss of yield on the tree production system.

6.1 Trees and Cold stress alleviation.

Few aspects of the role of trees in animal husbandry can claim to have attracted so much attention for so long as that of
the value of trees in reducing livestock production losses from cold stress; this is particularly so in areas where: i) livestock is kept outdoors for all or most of the year and; ii) cold stress can occur during long periods of the year and particularly when the quantity and quality of fodder are low. However disagreement has long prevailed, and still persists concerning the merits of trees in improving livestock production, and the level of costs which can be justified on tree establishment and management to provide for the expected increase in livestock production. Such disagreements are particularly rife in areas such as the British hills and uplands where: i) the extent of natural shelter from the topography and vegetation vary widely and where there are wide climatic variations within short distances; ii) the nutritional status of the livestock and the quality of livestock management are highly variable; iii) the availability of capital and labour varies considerably and is often low in comparison to the needs of possible alternative means of contributing to improved productivity (fencing, draining, reseeding, fertilizing, livestock housing). Trees take a long time to provide shelter; direct and indirect climatic influences on livestock are complex; the provision of shelter is often associated with concurrent changes in livestock management and farm policy; it is therefore difficult to separate the growing contribution of shelter to animal production from that of concurrent farming improvements.

6.1.1 The management of trees and livestock for minimum losses in animal production due to cold stress.

It should be clear from chapters 3 and 4 that the value of shelter to livestock depends on its location in relation to the natural and enforced distribution of stock at any time; on the
orientation of the shelter in relation to the winds' directions at any time; on the difference at any location in the availability and quality of shelter due to tree shelter compared to that provided by the topography and natural vegetation; and on the type and developmental stage of stock. Except where otherwise stated, the contents of this section refer to the UK hill and upland situation.

Timing of shelter.

For sheep, shelter is generally acknowledged to be necessary in harsh weather at lambing time which usually varies between February and mid May. The need for shelter at shearing time is not thought necessary in the UK although in some parts of the world, e.g. parts of S. Australia, it is thought to be important as sheep are vulnerable for c. 5 days after shearing to inclement weather (Geytenbeck 1962).

Although livestock physiological research (see Chapter 3) has identified other periods of the development cycle which are particularly sensitive to cold stress (the week prior mating, the 4 - 5 weeks after mating and the 6 weeks prior to parturition), there seems to be little suggestion from the literature and from farmers that shelter is necessary at these times except in extreme conditions; whether this is because it is just more difficult for farmers to be aware of the beneficial effect of shelter at these times is not clear. (The difficulties of devising good experiments on the subject were discussed in Chapter 3).

For beef cattle, autumn calving is more usual and if stock is outwintered, the availability of shelter during periods of inclement weather is likely to be important over the whole winter and spring period.
Location, type and orientation of shelter.

When sheep are outwintered on the open hill (as opposed to enclosed pastures of better quality), the extent of the need for artificial shelter depends on the extent to which the topography provides natural shelter from different wind directions. As Munro (1961) found, this varies considerably between areas with different topography and must also often vary considerably between farms within the same area. The density height and distribution of shrubs, particularly heather (Calluna vulgaris), which can be of considerable value in reducing convective, conductive (through ground insulation) and radiative heat loss (Grace et al. 1979) vary between different areas and according to management. Long, narrow, fenced shelterbelts are often unsuitable because of the generally low site quality and harsh climate for the trees, and because of the need to allow free movement for stock from one area to another in changing weather conditions; the resistance of such belts to wind is low and their maintenance, repair and regeneration for maximum shelter efficiency very difficult to achieve. Shelter blocks, which can provide shelter from any wind direction, are therefore more suitable, either square or circular (the cheapest in terms of fencing) or of various shapes which may be more efficient in terms of shelter provision (e.g. the Manx-leg block, Cadman 1963, Caborn 1965) but more expensive in terms of fencing. The sheltered area in the lee of the block is small, and unless the shelter is used only in the worst weather conditions, poaching and fouling can be a real problem (e.g. build up of parasites, Caborn 1968). The block can usefully be opened to stock for a number of years, but if it is to be a permanent feature, it must be closed to stock at regular intervals for a number of years to allow regeneration.
An alternative system was proposed by Hutch (1953) and Anderson (1953a, 1953b): a series of individually fenced small group plantings which would allow access to stock between groups; the regeneration of a number of groups would be possible at any one time without altering the overall efficiency of the shelter. This system does not seem to have been implemented in the UK hills, probably partly because of the higher fencing costs which would be incurred. There may however be more of a future in it if it was modified to be integrated with a system of Betula spp. and Alnus spp. (mixed with conifers) fallow aimed at providing a rotation of fuelwood and timber as well as improved soil conditions.

Shelter blocks or screens should be carefully sited after considering a number of factors: the quality and quantity of grazing within easy access from the shelter, the extent to which such grazings are kept free of snow by wind during storms, the ease with which stock may reach such shelter during storms, and the ease of access to the shelter by stockmen in severe weather when the provision of supplementary food is desirable. The areas close to the block which are liable to be sheltered should be as resistant as possible to poaching (i.e. well drained).

The long term quality of stockmanship is likely to make a big difference to whether a shelter block is efficiently used or not; stock can be trained (a long term process) to seek shelter when a storm is imminent (Kunro 1961), and the concentration of stock in specific sheltered areas is of great advantage to the shepherd compared to a situation where the sheep scatter in small groups in potentially dangerous locations (e.g. snow accumulation zones). For breeds with a strong home range instinct, it would be desirable to have several shelter zones scattered over the hill.
It would seem likely that the divergence of opinion within the hill farming community concerning the desirability of woodland shelter on the hill (Nichols 1957, Munro 1961) has to do with poor positioning of the woodland and poor design and maintenance of the structures frequently encountered (Murray et al. 1961, Caborn 1960), varying stockmanship skills, and changes in herd management since the time of planting of the woodland shelter; in their survey of 130 shelterbelts in the Lothians and Peebleshire (S. Scotland) Murray et al. (1961) found that only 25% of the belts had a satisfactory structure in terms of their fitness for their prime function of providing shelter, and 51% were completely unsatisfactory (4% were derelict and 20% rather unsatisfactory). At least on the mainly unimproved hill, there is usually a surplus of land and therefore the presence of shelterblocks or screens would only be likely to have a negative influence on the carrying capacity of the hill, from a fodder point of view, particularly, if they covered a large proportion of the more productive and better drained sites available.

The greatest value of artificial shelter to livestock is likely to be in situations where the stock are concentrated on specific enclosed areas of the farm, usually of better and improved productivity. This mostly coincides with the period of the year when greatest susceptibility to climatic stress can occur (flushing, tupping, post mating, prelambing and lambing periods); as the pasture is of improved quality, there is usually little inherent shelter provided by the vegetation (see section 3.1.3).

For several reasons, if the function of the woodland is primarily that of shelter, rather than also timber production, the width, structure and species composition of the woodland should be
a compromise between that required for the protection of the greatest area in the lee (see figure 4.11) and that required to make it possible for regeneration without clearfelling; the desirable width would therefore depend on the exposure and quality of the site and may vary from less than 20m on good sites to more than 40m on poorer and more exposed sites (Caborn 1957). However, if the topography, site quality and farm structure are suitable, the establishment of a new adjoining shelterbelt followed by clearfelling of the old one may be an easier way of maintaining shelter in the long run.

The greater the area protected against the wind, the less fouling and poaching is likely to occur for a given stocking density of sheep or cattle. There is little evidence however on the distribution of stock in relation to shelterbelts in wet windy conditions; while the wind speeds can be reduced to considerable distances from the belt depending on its structure, the rain shadow zone which may be more important to stock is very limited. A spread of stock in the sheltered area is important to the stock (reduced risk of disease, Whitelaw 1977) and to the pasture in two ways; fouling and poaching reduces the amount of early grassland - a scarce and valuable resource on many hill and upland farms; the fertilizer value of dung is lost from a greater area of grassland. There is also some divergence of opinion as to the value or disadvantage of high concentrations of ewes at lambing time concerning the mother lamb relationship. Amongst Romneys in New Zealand, Welch et al. (1970) found that at densities of 125 ewes ha⁻¹, with lambing spread over one week, there was a 10% mix up in ewe lamb relationships; this can be of importance in flocks where an effort is made to select for specific traits and is also a problem when the lamb
is taken up by another ewe which itself lambs subsequently. This disadvantage has to be balanced against the suggestion by Egan et al. (1972) that in S.W. Victoria (Australia), the successful use of shelter to improve Merino lamb survival depends on confining the ewes to areas of known shelter; without such control the provision of shelter has little effect on lamb survival. The advantage of close confinement is also implied by Alexander et al. (1961) for Merinos in New South Wales and suggested by Latson et al. (1962) for Corriedales in Western Victoria; the mother lamb bond can more easily be maintained, problem lambs helped to suck and more frequent suckling made possible. The extent to which such developments take place, and to which they are advantages or disadvantages must depend on behavioural, health, feed and management factors.

The role of shelterbelts in minimizing radiation loss on cold clear nights - important in cattle and particularly for calves and for lambs - is not likely to be significant except very close to the trees if the branches are low and overhanging. Shelterbelts are likely to have little influence on the conductive loss of energy to the ground which is likely to be much greater on closely grazed improved pasture than on unimproved pasture and can be a particularly important source of energy loss in twin-bearing ewes which spend a greater proportion of time lying down (Michael 1960).

The need for exposed grazing ground is desirable during warm weather when sheltered sites are liable to infestation with flies which can cause head irritation in sheep and mastitis in sheep and cattle; this is one of the main objections to the development of shelterbelts made by small upland farmers in the region between Glasgow and Edinburgh (Central Scotland Woodland project - pers. comm. 1980).
Some farmers complain that shelterbelts are a disadvantage in snow storms because snow accumulates in thick layers just where the sheep are sheltering. However this may be due to poor siting of the belt for the particular wind directions associated with such snow storms and with the structure of the belt (see section 4.3.1). Other farmers are glad for such a situation for they have a better idea of where sheep are likely to be trapped; more sheep may be freed per unit amount of effort than if sheep were scattered, sheltered over a wide area; similarly the effort efficiency of extra feed provision is greater where stock is concentrated. Access to woodland is particularly valuable for stock in severe weather. The ground temperature is likely to be higher than in the open, and conductive heat loss is consequently lower. In snowy weather, if the woodland is wide enough and of the appropriate structure (on the windward side and in canopy) the snow may be trapped within a short distance from the windward side leaving patches of clear ground for bedding and thereby also reducing the capacity for conductive heat loss. The loss of heat to the sky by radiation is reduced.

Grace et al. (1979) working on red deer in a Scottish Glen calculated the radiative heat loss for a clear night (using various assumptions about the skin, coat, aerodynamic resistance and about the proportion of the deer's body which is fully exposed to radiation loss to the ground and the sky): the radiative heat loss alone was 53 W for a 60 kg deer in the woodland where the ground, canopy and air temperature was 0°C; in the exposed situation, with a sky and ground temperature of -10°C and an air temperature of 0°C, the loss was 84 W (basal metabolic rate 73 W).

Thomas (1979) and Gumming (1980) report on the results of an ongoing trial in Sutherland which compares the performance of suckler
cows with calves (calving December - January) overwintering at two densities in Scots Pine and Larch mixtures alone with stock which have access to both woodland and a field and those restricted to a field with roofless slatted pens (all receiving the same food allowance). There were no consistent differences in calf birth weights between treatments. In some years, cows lost less liveweight and body condition in plots which included woodland and open field compared to those in woodland alone; those with access to slatted pens lost most weight and body condition. In one year, the calves on slats were an average 17.2 kg lighter at the end of the winter than those with access to woodland. However it is difficult to dissociate such differences from the differences in health and from the management which occurred between treatments. A blizzard in January 1978 caused much loss of life in outwintered stock throughout the highlands but had no effect on the cows and calves which had access to the plantations. There was no problem in finding healthy cows and calves in the forest but the area of woodland open to stock was small (12 cows in a maximum of 2.4 ha); however the main drawback is in the difficulty of finding and moving animals which have become incapacitated through illness or difficult calving (a change in calving date was therefore proposed for stock overwintering in woodland). Yet the minimum woodland area required by stock in terms of suitability of the ground surface (i.e. stock are at a disadvantage where the ground is poached to a certain degree) depends on the nature of the soils, the type of stock seeking shelter, differences in hoof pressure and the particular climatic conditions in any year (e.g. wet or frozen soils). In the Sutherland trial, the stock had to be removed from the plot which included field and woodland (density 10 cows ha⁻¹ for the total area but 30
cows ha⁻¹ of woodland within the total area) in December 1960 because of the very wet conditions (chance occurrence one in 25 - 30 years). Borrissov (1962) noted that in Aberdeenshire where winters are generally more severe than elsewhere in Scotland, and where extra feed is provided anyway, dense overhead tree shelter is particularly desirable. He suggested that in the more moderate climate (in terms of temperature) of Argyll, grazing availability is the more dominant factor in outwintering, shelter being of secondary importance.

The use of woodland for shelter can be a disadvantage to certain types of stock when these ingest parts of trees which may be toxic. Knowles et al. (1980) reported on evidence from the USA on bark and foliage of Cupressus macrocarpa and needles of Pinus ponderosa leading to abortion in cows when ingested; in New Zealand, there is considerable evidence that the ingestion of Pinus radiata needles lead in many cows to the delivery of aborted foetuses, or dead or weak small calves. In the New Zealand situation, it seems that the cows are most susceptible in their last two months of pregnancy and particularly so to wilted needles which are the result of pruning or thinning within 4 months before ingestion. There is no evidence that the reproductive performance of ewes is affected by P. ponderosa or P. radiata needles. The choice of tree species which are not toxic to stock, the appropriate timing of silvicultural operations for species which are toxic for a certain period after cutting and supplementary feeding away from toxic species should considerably reduce the risk of reduced animal production due to this factor when stock requires woodland shelter at sensitive periods of their reproductive cycle.

It seems that under British hill and upland conditions, the value of different kinds of shelter to different stock varieties in
different years and in different parts of the country defies quantification. It should follow however from Chapters 3 and 4 and from the previous discussion that given careful stock management, careful consideration as to the type of shelter required and as to its desirable location and orientation, livestock productivity should be improved. It is also likely that improved weather forecasting accuracy should enable stockmen to optimize on the value of woodland shelter.

In sheep, the provision of shelter can help to reduce ewe mortality, help increase lambing percentage and reduce lamb mortality. The lamb selling percentage is crucial to the economics of sheep farming operations (Barton et al. 1977). The lamb weight at selling time can be considerably increased, as can the lifetime performance of replacement stock (see section 3.1.3). For instance a higher birth weight of 0.4kg generally results in a higher weaning weight of 1 kg (ZSCL 1977). The lambing date may be able to be brought forward thereby enabling heavier lambs to be sold in the autumn and enabling tupping to take place in better conditions resulting in higher productivity. The provision of shelter may enable the conversion from traditional hill sheep towards more prolific and heavier breeds (Landale 1960). Further it may be possible to keep cattle where it has not been possible to do so before; it is recognized that cattle can help improve or maintain the productivity of pasture (Armstrong et al. 1972, Macdonald 1980). Sturdier lambs, quicker growth and improved mothering behaviour which can be partly enhanced by shelter associated with careful stock management, may reduce the incidence of loss to fox and hooded crows (Bannatyne 1977).

Landale (1960) suggested that of the more than two fold increase in productivity on a hill farm in S.E. Scotland between 1896 and 1960,
a quarter to a third can be attributed to the planting of appropriate shelterbelts. Michael (1960) showed that in 1955 (some weeks of snow and bad weather in February and March), pregnancy toxemia (a condition associated with double pregnancy and resulting in a high rate of mortality), occurred in 5% of the parts of surveyed hill flocks which had no access to woods while no cases were recorded in parts of flocks which had access to woods.

In parts of the world where the winters are more consistently severe for stock, and where the wind conditions and topography more regular, the value of shelter in cold stress alleviation is more easily quantified. On the windswept Canterbury plains in New Zealand, one farmer reported that the establishment of well designed and carefully located shelterbelts and woodlots to which livestock have access in severe weather (associated with well planned herd and pasture management in relation to shelter needs) has increased livestock productivity by approximately 20% (Wilson 1978). In a three day storm in one year, the shelter provided by the trees (which have a value in wood production terms as well) saved over 800 New Zealand dollars' worth of lambs from a 1500ewe lamb drop (Smail 1979). In the windswept district of Gippsland in Victoria (Australia), a farmer has calculated that a cost of 1210 Australian dollars, the establishment of tree shelter for a 20 ha paddock reduced lamb losses by an average of 5 to 10% (from 20%) giving an added annual gross return of 300 dollars; the cost saving in fodder each year for cattle with similar sheltered paddocks was 210 to 360 dollars because of reduced fodder needs (Australian Forest Grower 1980). Atchison (1976) reported on several estimates made by farmers in the Great Plains (USA) on the increased value in cattle production due to the
establishment of shelterbelts in years of bad winter storms, 8 dollars per head was claimed for one 800 feeder herd; he quoted Stoeckeler et al. (1949) to have reported that in Nebraska and South Dakota, tree protected feeders gained 15.9 kgs more in a mild winter and lost 4.8 kgs less in a severe winter in sheltered feeding lots.

6.1.2 Woodland requirements and implications for stock management.

Woodland out of bounds to stock.

When the shelterbelt or block is out of bounds to stock, forest management is easier though the benefits to stock are reduced. The site can be drained so that i) the growth of the trees can be greater and effective shelter established within a shorter time after establishment; ii) sites of lower quality (wetter) can be successfully planted. The regeneration of the woodland can be more easily carried out, and species which would otherwise be prone to damage (by browse, debarking, e.g. sycamore) introduced which may be desirable from the point of view of the structure of the belt. With a narrow shelterbelt, the silvicultural interventions have to be frequent so as to maintain the desired permeability and a foliage cover as far down the trunk as possible (unless underplanting is resorted to).

The eventual value of the resulting timber would be low both because of frequent large knots and because of the exposure to wind leading to slower growth and poor form.

To combine commercial forestry with shelter provision, i.e. to get a reasonable return from the wood, the width of the block has to be large enough so that: i) a large proportion of the width of the block is sheltered (mutual shelter) and the trees of good form, even when part of the block is felled and replanted to maintain the
permanence of the shelter; ii) because of the impermeability of the block to the wind, the downward wind turbulence is reduced and the effectively sheltered zone is greater than that in the lee of a dense narrow belt (see section 4.2.1).

The appropriate sitting of the block of woodland in the topography in relation to the grazing ground would be crucial if a greater area is hoped to be protected than that which would be protected from a dense narrow belt. It is quite likely that only some farms would have the appropriate combination of suitable topographical features and patterns of land of different quality (e.g. suitable for improved pasture resistant to poaching) for large woodland blocks to provide useful shelter. The presence of such large blocks of woodland would reduce the flexibility of stock movements and management in the wake of changing wind directions as seen above. Woodland to which stock have access.

This form of shelter can be theoretically rationalized as being the most valuable to stock and is appreciated as such by many farmers (e.g. Borrissov 1962, Mutch et al. 1980). However it presents several problems in terms of woodland management.

The sites on which such woodland can be established and managed are more restricted than those which support fenced-off woodland: open drain furrows are not suitable where cattle are introduced as these damage the drains (Cumming 1980), reduce their effectiveness and damage tree roots (increasing the likelihood of fungal attack); they are also unsuitable for young calves and lambs since these may get stuck in the furrows and die. Therefore reasonably well drained sites are necessary. Well drained sites are also required because the trampling of the soil in wet conditions is detrimental to the soil structure and as on poorly drained sites the tree roots are close to the surface, the trees may suffer. When the soil is frozen
however, the introduction of stock within even poorly drained sites should be possible without adverse consequences.

In situations where no direct financial returns are expected from the woodland shelter, the cost of establishment of the woodland shelter and of its maintenance should still be less than the expected returns in terms of improved animal production. Hence the longer the life of the shelter, the better; yet some farmers insist on sheltering such densities of stock in their woodland shelter that the badly poached soil leads to an early death of the trees (e.g. Hutch et al. 1980). If the value of shelter is so important and justifies the initial investment, it should not be acceptable for the shelter to be merely a temporary feature; this is particularly so where developments which have taken place on the farm (e.g. change in breed type, change in parturition date, improved pasture at certain locations) are dependent on the provision of shelter. The establishment of a number of shelter blocks may therefore be advisable so that a rotation of blocks open to grazing is possible to reduce the extent of poaching and to enable regeneration to take place from time to time.

In situations where a return from timber is required to justify the costs of woodland establishment, a careful assessment of the anticipated reduced yields and higher woodland management costs (therefore lower returns), and of the expected improved livestock production is required.

The trial in Sutherland with cattle overwintering in a Forestry Commission plantation (precipitation c. 850 mm yr$^{-1}$, firm well drained ground) has revealed some important considerations which should be taken into account. For that particular site, the density of cattle should be considerably less than 30 cows ha$^{-1}$ of woodland (where there is also access to a field). Preliminary calculations indicate an
average loss of 10% in basal area increment compared to control sites, with a greater loss close to the woodland edge and close to feeding troughs (where at a density of 30 cows ha\(^{-1}\) the increment was 43% of that in the control - Lines 1979, Cummings 1980, Lines 1981), and with the possibility of slight gains in increment beyond 50 m from the edge (perhaps a manurial effect) (Lines 1979). The feeding troughs should be outside the woodland except in bad weather; when inside, a decision has to be made as to whether production of part of the woodland will be considerably reduced and the feeding troughs kept in one place, or whether it is better to move the feeding troughs around so that a greater area of woodland is affected to a lesser extent. In plots which contained pure Scots pine, mixed Larch and Scots pine and a few Sitka spruce, the small Sitka spruce groups were much sought after during snow storms and at the time of calving (Cummings 1980).

A deliberate decision should be taken to choose for the main tree crop, species which have a deeper rooting habit (e.g. Scots pine, larch) as opposed to shallow rooting (such as Sitka spruce), as even on well drained sites shallow rooting trees are likely to be more affected by stock trampling. The choice of species, in terms of suitability for shelter, and the pattern of planting should help in either concentrating stock, or spreading stock, with consequences for the tree crop and for livestock management. Again the rotational use of several blocks of woodland or parts of woodlands would be desirable. The density of stock which would be acceptable in woodland shelter will vary according to the trampling characteristics of different types of stock. The static hoof pressure of sheep is smaller than that of cattle: Lull (1959 - quoted in Borrissov 1962)
gave a figure for the ratio of hoof pressure of sheep to that of cattle of 1 to 2.5, while Finol (1970) gave one of 1 to 1.4. The area of ground covered in a day by different stock (degree of movement) also contributes to the degree of trampling experienced by a site.

In the spring, an early warm period may set the sap to rise; when this occurred in the Sutherland trial, of the conifers, Scots pine and Sitka spruce (20 years old) were found to be stripped of bark (as were all the broad leaves) (Cumming 1960, Lines 1961). Evidence suggests that some specific cows may do more harm than others, or at least may do so before others are tempted. A hard decision has therefore to be made if the weather is harsh after the sap has started to rise, as to whether the tree crop is going to be partly sacrificed for the continued well-being of the stock.

The potential value of the tree crop could also be considerably reduced where concentrations of dung and urine occur (Borrissov 1963), since a change in soil pH may lead to an increased likelihood of root fungal attack (e.g. by *Fomes annosus*), while mycorrhizal associations could be affected. Lower tree vigour could also lead to an increased incidence of infestation by insects (Lines 1977). In grazed Austrian Larch plantations, trees on the more heavily grazed sites have been found to be attacked by *Semaria deniana* and *Coleophora laniella* (Schimitschek 1966 in Adams 1975). In parts of Western Australia, *Pinus radiata* shelterbelts are susceptible to *Phytophthora cinnamomoni* attack beyond the age of 20 years; the susceptibility is increased by compaction and camping of grazing animals and by some extract of cattle urine which stimulates the sporulation of the fungus (Batini 1979).

The successful integration of timber production with the provision of woodland shelter requires a very careful assessment of local
conditions, both in terms of timber production and management alternatives, and in terms of livestock management possibilities. The various partners associated with such integrated systems of production and management must be aware of the risks which are involved in terms of the possible reduced timber production, and the possible need to expose livestock to harsh weather if the tree crop is jeopardized at any time. The site specific nature of the resulting interacting processes in such integrated systems, as well as the long term delay in the outcome of some of the interactions, make it as yet impossible to predict with any degree of precision what the various costs and returns are likely to be. The outcome of the production functions of the integrated system would in any case be very sensitive to management input.

6.2 Trees and the alleviation of heat stress.

Although the need for shade in alleviating heat stress in livestock is no doubt appreciated by livestock owners in areas where heat stress occurs at certain times of year, it may not be realized to what extent shade can directly or indirectly contribute to improved production. Specialists in the field of animal production (e.g. Robertshaw et al. 1976) do suggest that shade is of obvious benefit to livestock; however attempts to quantify such benefits under field conditions suffer from the same problems as those attempting to quantify the value of shelter in the alleviation of cold stress: it is not possible clearly to dissociate management, health, feeding and watering factors from those of heat stress in their relative influence on animal production. Although there are other means to alleviate heat stress (provision of water for drinking, wallowing, showering, artificially cooled rooms for
specific times of the reproductive cycle), shade provided by trees is one means which can concurrently provide other useful commodities (e.g. wood, fodder).

6.2.1 Tree shade and minimization of heat stress.

Many authors (e.g. Robertshaw et al. 1976, Kirkby 1976) suggest unconditionally that the provision of shade reduces the heat load on livestock. While this is true, the extent of the reduction in heat load depends on the contribution of the short wave radiation input to the overall heat input to the animal, and this varies considerably in different climatic conditions and for different breeds. Further as section 4.4 outlines, different types of tree canopies and spacings are likely to have a considerable difference on the animals' convection, evaporation, conduction and radiation regimes (see also Fig. 6 in Annexe I); again the various mechanisms by which heat is gained or lost vary in their relative contribution to the heat balance of stock for different types of stock and climatic regimes.

Short wave radiation.

The reduction in heat stress through the provision of shade reducing short wave radiation input alone will vary considerably between livestock of different breeds, ages, and body condition because of their widely different surface albedo and insulation characteristics (Chapter 3) (Mount 1979). Dense canopies are best at reducing the short wave radiation input and the leaf period has to coincide with the sensitive periods of heat stress. In areas of the world where the periods of heat stress coincide with the time of year when the sun is at its highest point in the sky, wide diameter crowns are desirable so that stock can shelter under the crown.
In areas where the value of production per unit area is high and the requirements for pasture production are for light canopied tree species, a few scattered individuals of dense canopy species may be desirable.

**Convection.**

Wind is generally believed to be desirable to enable losses of heat by convection. A surface temperature of Merino sheep fleece of 90°C (quite possible under high short wave radiation input) in still air is reduced to 60°C in a matter of minutes by a wind of 5 m sec\(^{-1}\); desert winds are common in the heat of the day (Mount 1979). Preston *et al.* (1974) referred to a few experiments and trials during hot periods in the S.W. USA which showed that increasing wind speeds (by reducing shelter in pens or by artificial fanning) lead to better beef production performance (increased feed intake and daily gains, and improved feed conversion). This suggests that clear-boled or high-pruned trees with a wide canopy are desirable so as to enable least reduction of wind speeds at stock height. Wind speeds may further be increased under the canopy compared to open ground by an appropriate tree planting pattern (section 4.2).

The appropriate location of shade trees in the topography would inevitably be a compromise between the stock requirement for the trees to be on a site suitably exposed to wind (rather than in depressions which may be heat traps) and the trees' requirements for both access to water for the roots and for least vapour pressure deficit. So as to minimize the influence of livestock crowding on convection heat loss reduction, there have to be an appropriate number of trees for any given herd size.
**Evaporation potential.**

Increases in relative air humidities considerably reduce the ability for livestock to loose heat by evaporation through either panting or sweating (Preston *et al.*, 1974, Kount 1979). In N.W. Oklahoma, McIlvain *et al.* (1971) found that the increase in live-weight gains in steers provided with shades (artificial) compared to steers without access to shade, were greater in periods of high atmospheric humidity. Hence daytime heat stress in humid environments may be reduced by stand densities which combine increased vapour saturation deficits (see section 4.3.2) without an increased heat input.

**Conduction heat relationships.**

If the livestock rest by lying down (probably true for the sensitive period of mothers in late stages of pregnancy) the lower the soil surface temperature (relative to body heat), the greater the amount of heat which can be lost to the ground. Clearly the tree spacing and crown characteristics which lead locally to the lowest soil surface temperature (as described in section 4.4) enable the maximum heat loss by conduction. It may be important to have enough cool ground surface area so that each individual may move from time to time as the soil surface reaches temperature equilibrium with the body surface temperature of the stock.

**Long wave radiation.**

Theoretically it can be shown that heat losses through long wave radiation to a cold clear sky or cold ground can occur (see section 4.4). Further cattle have been shown to behaviourally respond positively to shades which enable long wave radiation loss to the sky compared to shades which merely prevent short wave radiation inputs (Kelly *et al.*, 1957). The maximization
of long wave radiation losses can therefore be provided by a pattern and density of tree crowns which compromise between:

- the ground area shaded by the crowns being exposed to a considerable amount of cold clear sky (and at least the coldest area of the sky during the hottest part of the day, which is at a compass point opposite to that of the sun and at right angles to its direction) and,

- as little as possible of hot ground from which long wave gains may occur.

Some people (e.g. Tree Farmer 1976 p 7 - see section 6.2.3) suggest that as high a crown as possible above the ground is desirable so that the shade moves across the ground as much as possible. This may however not be desirable for the minimization of heat stress where the soils are able to absorb radiation and store the heat so that the shaded ground is not only an area to which stock cannot loose heat but from which it can gain heat; this would be particularly important in the case of livestock types whose underside characteristics are particularly useful for long wave radiation loss and/or particularly sensitive to long wave radiation gains.

Enough shaded area should be provided to prevent crowding. The sight of livestock crowding under scarce available shade is common in many countries where the tree cover has been reduced over the years (e.g. Ferlin 1977). The extent to which livestock is likely to respond to crowding as a result of heat stress must be influenced to some extent by aspects of social behaviour which is likely to vary for different breeds. Nevertheless some suggest that for steers, a minimum of c. 6 m² of shade is required per animal (Ittner et al. 1958 quoted in McIlvain et al. 1971) while
others suggest there are no significant effects on beef weight gain between the provision of 2.5 m$^2$ per head and 18.5 m$^2$ per head though a slight tendency to improve the conversion efficiency of feed may occur with an increasing shade area (Freston et al., 1974). However neither study provided any indication of the relative contribution of reduced short wave radiation and long wave radiation loss to heat stress alleviation.

6.2.2 The direct benefits of shade.

A few examples of the direct benefits of shade on livestock production have already been mentioned in section 3.1.3. Appropriate tree shade provided at the right time of year at the correct location should contribute to a higher reproductive rate in otherwise heat stressed livestock (earlier puberty, higher conception rates, more regular fertile periods, lengthened reproductive life, reduced embryo loss, higher female to male ratio) and higher rates of survival in the offspring (mothers in better condition, easier parturition, larger and stronger offspring, higher milk yields and therefore shorter sensitive period for the offspring - see section 3.1.3).

The provision of shade has indeed been found to increase the reproductive performance of cattle (Vincent 1972); increases in the survival rate of lambs are reported in the steppe regions of S. Russia (Kasjanov 1965), for summer born lambs in N.W. Western Australia (Korgan et al., 1972) and strongly implied for Peppin Merino in N.W. Queensland (Hopkins et al., 1980). As calving, lamb marking and kidding percentages are usually very low in the tropics (e.g. lamb marking percentages of 35 - 40% in tropical Australia, Williamson et al., 1978) any increase in the reproductive rate and in the young
survival rate considerably increases the potential for useful production offtake (milk or meat) since at such low reproduction levels, the proportion of replacement stock required to total stock born and which survive is high.

The full potential of shade trees in improving livestock production through increased reproduction rate, young survival and individual performance can only be achieved by locating the shade trees in the grazing areas which are used at the times of year when livestock is particularly sensitive to heat stress (includes for sheep and goats also the areas where the stock is located at shearing time). In areas where transhumance or nomadism are the predominant form of herd management, the grouping of births in time would be crucial to the cost or effort effectiveness of production improvements through the provision of shade trees where the costs or efforts involved in creating and managing stands of shade trees are high.

The spatial integration of water provision, pasture availability and shade provision, and the appropriate herd management at the sensitive period prior to and following parturition is also likely to be crucial for the maximisation of production. Shade trees need to be close enough to water that the young who follow their mothers out of the shade to drink are involved with minimum exercise; proximity to water also enables the young to follow their mothers back to the shade rather than die of exhaustion if the distance involved is considerable (e.g. a situation found with sheep in N. Western Australia, Morgan et al. 1972). The availability of adequate forage close to the shade groves (and therefore the requirement for conservation of fodder in areas which are likely to be otherwise preferentially grazed) for the period prior to parturition would enable the heat stress particularly associated with
exersion at a time of high metabolic activity to be reduced and therefore lead to better condition in the mothers, easier parturition, higher birth weights and better overall survival prospects. Further by also providing adequate fodder close to the shade trees for a period subsequent to parturition, the mother-offspring bond would remain strong enough that the mother would return at suitable intervals to the shade to suckle the offspring, and the offspring may be able to suck during the period when the mother is protecting itself in the shade, compared to unshaded situations where the offspring is unable to suck during the heat of the day due to thermoregulatory exertions (see section 3.1.3, Hopkins et al. 1980).

Individual production can also be increased by the provision of shade. Live weight gains have been shown to be improved in sheep (Kasjanov 1965) and in cattle in several parts of the world (gains of the order of 5 to 15 kg or more per steer per summer, e.g. S. USA McIlvain et al. 1971, Preston et al. 1974, Australian Tree Farmer 1976; improved milk yields and greater wool production have been reported (Goldson 1973, Hopkins et al. 1980, Kasjanov 1965). As the conversion efficiency of fodder can be improved by shade provision (Preston et al. 1974), livestock production per unit amount of available forage could increase considerably. The availability of shade trees should enable in some situations a change in breed to less heat tolerant but more productive types.

However for shade trees to be of maximum benefits, the grazing management should take into consideration the natural grazing patterns of livestock: in many sub-tropical and tropical regions, livestock are grazed solely during the day rather than at least partly at night (Webster et al. 1980), the latter situation leading to greater feeding intake and greater production.
6.2.3 The indirect influences of shade.

Timing of mating and parturition.

The choice of when to plan for parturition is often a compromise between the likelihood of successful mating and the desire to have the best conditions for the growth of the young. In one set of observations in N. Western Australia, 94% of lambs born in winter survived past the age of 6 weeks and their average weight at 5 months was 15 kg; on the other hand only 72% of summer born lambs survived mainly because of heat stress, but they weighed 23 kg at 5 months (Jorgan et al. 1972). Hence the use of shade trees associated with controlled mating could help in several stages of the reproductive cycle to optimize the timing of mating and parturition. In the N. West Australian example, carefully sited shade trees should enable a higher proportion of summer born lambs to survive and therefore farmers who otherwise work on a winter lambing period may, with the introduction of shade trees, profitably change the mating time of their sheep.

In the arid regions of India, it is suggested that the provision of shade (along with other improved management inputs) would help to change the breeding (conception) season in sheep from July/August to March/April; this should increase production as August - September born lambs have higher survival rates and better growth (which also results in improved performance in adults) than winter born lambs (due to higher milk yields, more and better fodder at that time of year) (Acharya 1980, Singh 1980). Acharya (1980) also suggested that shade could reduce the seasonability of breeding in buffalo.

In transhuming and nomadic situations, if such changes were to take place, careful forward planning and coordination would be required so that the locations for the establishment of shade tree groves are in areas where the herds (which have a changed timing of
the reproductive cycle) are likely to be at the heat stress sensitive periods.  

**Water demand.**

It would be expected that good grazing management (timing of the spacial distribution of available fodder) combined with the provision of shade could reduce the need for water (see section 3.1.3). In New South Wales, Wilson (1974) compared the water consumed by Merino sheep which had access to shade provided by galvanized iron shelters with Merinos which had no access to such shade, in natural pastures over the seven summer months; shade provision reduced water turnover by a maximum of $0.3 \text{ to } 0.5 \text{ l day}^{-1}$ out of a total intake of $3 \text{ to } 3.5 \text{ l sheep}^{-1} \text{ day}^{-1}$. Unfortunately neither the density of sheep per shaded area nor the exact design of the shade shelter are known, so it is not possible to know if improvement in shelter design and density would have reduced water intake further; the sheep may in any case not have reached the thermal condition where much increased water intake was necessary to maintain the temperature within the thermoneutral zone.  

A lower water demand per livestock unit would reduce the required density of watering points and therefore the costs of production per unit area and/or would increase the area which could be grazed from a limited number of water points. For instance if the maximum distance which stock could travel away from a watering point was 15 km where no shade was available, and if the provision of shade increased this distance to 20 kms, the grazing area would increase from $706 \text{ km}^2$ to $1156 \text{ km}^2$. A shortage of watering points often limits the areas which can be grazed in dry regions (eg. see section 7.5 for Rajasthan).  

**Shade and grazing management.**

Active herding is usually necessary for good pasture management, to control grazing pressure in space and time; the provision of
shade trees should further help make this possible in areas where herding alone would be unsuitable due to livestock being heat stressed in those areas which need to be grazed during hot periods. Where stock are not herded, for instance in the S. plains of the USA, Kelly et al. (1971) suggested that it might be profitable to remove tree shade in areas which are overgrazed, and to provide adequate shade in ungrazed areas.

**Disease and health.**

Shade, by helping to improve the health of livestock, should contribute towards greater disease resistance. The availability of shade at some distance from watering points can also reduce the likelihood of disease which is promoted by the close association of stock with water bodies, as livestock without access to shade can spend the hot part of the day near watering places or in the water; stock with access to shade spend less time close to water (Ilvain et al. 1971).

Appropriate planting patterns and densities, and herd management may be important in not allowing important build-up of parasites. High concentrations of stock per unit area of shade, particularly if the shade does not move (low crown and therefore no regular drying and sterilization by the sun), enables the build up of dung which is likely to increase disease opportunities (Tree Farmer 1976). If the trees are located in an area protected from the wind or if they reduce wind speeds, the concentration of head flies and other insects may be detrimental to the well being and production of stock and production; this is so in Britain for sheep whose dung - soiled fleeces are particularly attractive to the sheep maggot fly (Thomas 1949).
Lightning dangers.

It is claimed by many livestock owners that the likelihood of stock being killed by lightning is greater when they shelter during thunderstorms under scattered trees which get struck compared to when remaining in open ground (e.g. in parts of Brasil, Leite 1981 pers. comm.). The losses can be particularly important where the behaviourally dominant stock chooses the most dangerous position close to the trunk, and is also the most valuable stock of the herd (e.g. the Herens breed in S.W. Switzerland). Appropriate herding prior to thunderstorms may minimize this problem.

6.2.4 Establishment and management considerations.

The planting of trees solely for the purpose of shade may be economic: at prices prevailing in 1965 - 1969 for beef in the S. Plains of the USA, the increased value of added weight on each steer each year due to shade was c. 5.00 dollars (McIlvain et al. 1971). Even if a tree provided only enough shade for one steer, the costs of planting trees and protecting them individually would be well below the value added in beef production given that the protective life of trees would probably be more than 30 years.

However in many situations, the planting of groves for shade could be coordinated with the desirability for specific areas of pasture to be rested for a few years, or with tree fallow requirements. Protection could be achieved either by rigorous herding or by fencing off the area; where available, grass could be cut within the enclosure where the ratio of unit value of fodder per unit value of labour is high; or it could be coordinated with the establishment of fodder or fuel tree plantations.
In contrast to temperate areas no report was found, for the tropics and sub-tropics, on the detrimental effect on tree health by the concentration of urine and dung which occurs under shade trees.

6.3 Live hedges and areas dangerous to stock.

6.3.1 Areas dangerous or difficult to manage for stock rearing.

In regions of the world where sheep graze extensively, are out wintered and snow falls occur, areas which are particularly sheltered from the wind and which accumulate large quantities of snow (e.g. gullies) can act as death traps to stock which get smothered by snow and suffocate. It may be economic to fence such areas off to prevent livestock losses; where the value of a unit area of summer grazing is low (summer forage surplus) and the site potential for wood production is reasonable, since a large proportion of the costs of plantation establishment is that of fencing, the subsequent planting of such dangerous areas can result in overall increased production for a farm unit. Such developments have taken place on some farms north of Dumfries (S.W. Scotland). The same applies to areas of a farm in hilly districts, where stock may congregate, but the costs of shepherding of such areas are too high to be justified by the returns: for instance slopes which are not visible from the normal "beat" of a shepherd (e.g. some farms in the Scottish Borders).

6.3.2 Live hedges.

In temperate regions, when the ratio of unit cost of labour to unit value of product was low, more farms than at present were of a mixed type and a grazing rotation on small fields was required, the
use of stockproof hedges which also provided firewood was common. Species which can propagate by cuttings or layering and which are able to coppice or thrive when the stem is cut to a certain thickness for layering (e.g. *Crataegus* spp.) are particularly useful. Thick hazel (*Corylus* spp.) hedges were still used and managed as stock proof barriers in the late 1950's in certain parts of the French Jura (Rieben 1957). Species which provide by-products are particularly valuable - e.g. *Corylus* nuts and wattling sticks. Many tree and shrub species are used for stock barriers, either alone or by providing live fence posts to support wire, in several parts of Central America, particularly Costa Rica (Sauer 1979) and in parts of East Africa and S.E. Asia (Williamson et al. 1978). Their value in animal production can be increased if the trees provide useful shade or shelter from cold winds and dry weather forrage out of reach of the stock (by pollarding at the appropriate height e.g. *Gliricidia sepium*). Lists of some useful species which are commonly used in the tropics are provided by Williamson et al. (1978) Sauer (1979) and Weaver (1979), while for the arid and semi-arid zones, several species of *Euphorbia* spp., which are easily propagated, are said to be promising (Burley 1980).
CHAPTER 7

Background to the Role of Agro-Silvopastoralism in Western Rajasthan

Prosopis cineraria (Linn.) Macbride or Khejri and other trees and shrubs, have played a significant role in the rural economy of the dry N.W. region of the Indian subcontinent (Mann et al. 1980). Their major products include fodder, fuelwood and timber. Several tree and shrub species and in particular Khejri and Zizyphus nummularia Burm. f. or Bordi have been encouraged by farmers because their impact on grain yield and forage production is believed not to be detrimental at least up to a certain density of trees or shrubs. Due to increased pressure on natural resources and in order to help meet the increasing food, fodder and fuel requirements, the suggestion has frequently been made in recent years that further development of agroforestry and silvopastoral systems in the cropland, rangeland and forest areas would lead to higher levels of sustainable production in the livestock and crop sector as well as provide an increased supply of fuelwood. Mann et al. (1982) stated: "on a long term basis the plantation of this valuable tree (Khejri) will help in the economic development of Western Rajasthan". Ahuja (1977) also stated that fodder trees and shrubs (woody perennials or fodder WPs from here on) are an important source of nutritious leaves and pods which are rich in proteins and minerals, particularly during the lean period of the year, and these therefore increase livestock productivity. Ghosh (1983) stated that calculations show that fodder WPs can with proper management meet the dry season fodder demand on the basis of currently existing vegetation.

Relying on the extensive literature which has been published on
various aspects of agro-silvopastoralism in Western Rajasthan it was felt useful to attempt to evaluate critically some of the aspects of its contribution to livestock and fuelwood production. This is particularly so since references concerning its benefits are increasingly being made in the international literature (e.g. Leakey et al. 1980, Lundgren 1982, Mann et al. 1980a, Nair 1984, Torres 1983 and Tejwani 1979). Yet a closer scrutiny at the Indian publications, and particularly at those from CAZRI, indicate that there are considerable discrepancies between sources concerning the actual and potential level of the contributions of fodder WPs to the farming systems. Uncritical reference to the alleged benefits of fodder WPs and of agro-silvopastoral combinations in Western Rajasthan could mislead researchers and development agencies on the potential benefits which the introduction of such species and technologies could have elsewhere.

Much of the literature on agroforestry and on other rural issues from Western Rajasthan has been gathered by the Central Arid Zone Research Institute (CAZRI) in Jodhpur. For the purposes of this case study, unless otherwise stated, the area referred to is that of Western Rajasthan (W Rajasthan) (see Fig. A.4.1). T (total) Rajasthan and E Rajasthan refer to the whole of Rajasthan and to Eastern Rajasthan respectively. The western side of the Aravalli range, running NE-SW is the geomorphic as well as the climatic (500 mm isohyet) eastern boundary of W Rajasthan. The area included here covers c. 208 220 km² (Mann et al. 1977a) (see Appendix 4).

Many discrepancies and errors were found in the publications from
various authors. Where possible these have been corrected or the most likely set of information presented but the possibility cannot be excluded that further significant errors or gaps in the presentation of evidence by other authors and quoted here have still been overlooked. Where possible, all assumptions and calculations in the main analysis refer to 1971-1972.

7.1. Climate and edaphic factors.

The average annual rainfall ranges from c. 100 mm in the N.W. to c. 450-500 mm in the E. of the area (Krishnan 1977). Between 85 and 95% of the annual precipitation occurs between June and September in various parts of the area. The inter-annual variation in precipitation (P) reaches more than 70% in the drier parts. The hottest period occurs during May and June with a mean maximum of 40°C while the winter has cold nights from December to February with frosts occurring commonly in some districts and has mean diurnal variations of 14 to 16°C. Annual mean potential evapotranspiration (EPT) rates range from c. 1650 mm to 2100 mm giving P/EPT ratios of c. 0.05 to 0.26 (arid and semi-arid zones according to the UNESCO classification of arid zones, Burley 1982).

Soils are variable in nature and have a low water holding capacity (see Appendix 5). Levels of available phosphorus range from "low" to "high". Soils generally have a pH of more than 8 and some areas are affected by salinity. A number of topographical units occur and these include alluvial plains, saline depressions, sand dunes, rocky or gravelly pediments and hills (Tejwani 1983).
7. 2. Human population.

In 1971, 82% of the 10.2 M people of W Rajasthan lived in rural areas. Between 1961 and 1971 the population increased by 27.95% (Malhotra 1977).

7. 3. Cropland trends.

In the early 1950's following land reforms, the abolition of feudal land ownership, the distribution of ownership rights to tenants and landless people, the introduction of much lower land revenue rates for cropland than those existing under the previous feudal system, and following the abolition of levies on grazing lands and livestock (Jodha 1980), considerable changes took place in the land use patterns of W Rajasthan. Hence, partly due to the increase in human population, but also because of the reduced cost of land use, the net sown area (ie. not including the area cropped a second time in the year) increased between 1951 and 1961 by 44.6% and by an additional 12.6% from 1961 to 1971 when 44% of the area was under cultivation (Malhotra 1977, Mann et al. 1977a, see Appendix 6). However only 45% of the cultivated area was said to be suitable for sustained cropping (Singh 1978), resulting in a general annual decline in average crop yields (Malhotra 1977).

Problems of reduced fallow periods resulting in lower soil fertility, of increasing salinity due to irrigation and of shifting sand covering fertile lands have been prominent (Jodha 1980, Raychaudhuri 1978).

Jodha (1977) showed that during 1970-1971, in most districts more than 80% of the area of private holdings was actually cultivated. The average area under private ownership was 59%, ranging from 13% in the driest district to 89% in a district more suitable for cultivation.
Hence the private area under fallow, an important way of allowing the land to recuperate its productivity and enabling part of the holding to produce some forage, the consumption of which can be controlled, is small. Jodha's data also showed that in the 7 districts (out of 11) which receive a higher rainfall, over 95% of the area is cultivated on holdings which are smaller than 5 ha and these comprise 40 to 70% of all the holdings in these districts.

The frequency of drought is an acute problem. For an area near Jodhpur which is fairly representative of average conditions in W Rajasthan, between 1899 and 1976 (78 years) there were 43 mild drought years (50% reduction from the grain yields obtained during a rain "surplus" year), 19 drought years (75% reduction in grain yields), 8 "surplus" years when all the crops matured. In a rain surplus year, mean fodder crop production reached 1515 kg/ha while in a moderate drought year and a drought year the yields reached 605 and 70 kg/ha respectively (Bharara 1980).

It therefore seems clear that crop husbandry in the area is a high risk enterprise. If all the irrigated potential is achieved by the end of this century, including water from the Rajasthan Canal and other ground water resources, only one quarter of the area under cultivation in 1971 will be irrigated (Mann et al. 1977b) leaving the majority of croplands in a very marginal state of production.

7. 4 Trends in livestock population and grazing lands.

Since the abolition of the feudal system under which a considerable degree of grazing control is said to have existed and grazing taxes were levied, effective penalties and taxes on
indiscriminate animal grazing have disappeared. On the other hand the prices for wool and ghee increased 3.5 and 5 fold respectively between 1950-51 and 1964-65 (at 1976-77 prices) (derived from Jodha 1980). Further, the market for goat exports to the Middle East has flourished (Saxena 1983).

The grazing lands effectively comprise the majority of the area which is not cultivated, "barren" or put to "non-agricultural uses" (Ahuja et al. 1975), i.e. 41.3% of the total area in 1971 (derived from Mann et al. 1977a; see Appendix 6). Because of uncertainty about the allocation of some land to the "baren" or to the "uncultivatable waste land" categories in the 1951 records, the available area for grazing in 1951 covered either 10.47 or 12.0 M ha. It had decreased to 9.639 M ha in 1961 and 8.606 M ha in 1971 (derived from Mann et al. 1977 a,c). Most of this loss is likely to have come from the better grazing lands. Jodha (1980) stated that the livestock density per ha of grazing space was 0.36 and 0.62 Animal Units (AU) in 1951 and 1961 respectively (see Appendix 7a for conversion factors to AU). This increase in stocking density was against a background of precipitation which was below the long-term "normal" levels in 1950-1951 and well above "normal" in the years leading to 1961 (Krishnan 1977). From 1961 to 1972, however, the livestock population increased from 13.9 M to 16.3 M even though 1967-1971 were years of continuous drought.

Appendix 7A shows that by converting livestock numbers to Adult Cattle Units (ACU = 300 kg animals) and by using certain assumptions concerning the ratio of adults to young and their respective weight, there was in fact no increase and perhaps even a slight decrease in ACUs between 1961 and 1972. Using different "grazing units" used by
other authors, the same pattern emerges; this is because buffalo, sheep and goat numbers had increased by 14.6, 18.5 and 69.6% respectively while cattle numbers had decreased by 21%. The use of the metabolic liveweight (ie. $W^{0.75}$) (Macdonald et al. 1981) is a more meaningful indicator of grazing/browsing demand than liveweight. The conversion of the respective livestock types to ACUs using $W^{0.75}$ also indicates a slight decline in grazing demand.

However considering the reduction in effective grazing area, the stocking density increased from 0.37 or 0.42 ACU ($W^{0.75}$) per ha in 1951 (see Appendix 7B) to 0.66 and 0.73 ACU ($W^{0.75}$) in 1961 and 1972 respectively (see Appendix 7A).

About 80% of the grazing lands have been classified as "Poor" to "Very Poor" (Ahuja 1975). The area of rangeland needed to "maintain" an ACU on a sustainable and a year long basis for "Poor", "Fair" and "Good" condition classes is stated to be 8, 6 and 5 ha respectively. Hence according to the figures supplied, if the livestock population had to rely on rangelands alone for their feed on a year long basis, their numbers would have been about 5 times too great for sustainable production and safeguard of the grazing lands themselves.

Kalla et al. (1980) stated that in 1970-1971, the total fodder "requirement" for W Rajasthan was 41.08 M "tons" (?W) while the supply was only 17.33 M "tons". In 1977 Ahuja et al. (1980) estimated that in years of "normal" (ie. average) rainfall, the supply of forage amounted only to about 60% of "requirements", while Paroda (1978)

---

Note 1 For the significance of codes related to plant weights see Appendix 11.
stated that the livestock "are unable to get even one third of what they need for a maintenance ration".

Clearly suggestions that livestock were receiving considerably less food than required purely for maintenance are completely unrealistic. A realistic analysis of fodder supplies and demand needs to look at the possible alternative sources of fodder such as crop residues, tree fodder, feed concentrates and fodder crops. Furthermore, not all the livestock remain in the area over the whole year. Acharya (1980) stated that irrespective of the severity of the climate, 80% of the livestock migrate for a number of months each year from the arid districts of Barmer, Jaisalmer, Pali, Jodhpur and Bikar (see Map 1, Appendix 4) to neighbouring districts and to Madhya Pradesh and to a lesser extent to Gujarat and Haryana.

Even though there seems to be a severely inadequate evaluation of the feed requirements for the various types of production of the area's livestock population, and of the feed availability, it seems to be generally agreed that the high livestock densities are leading to an overall decline in the productivity of the vegetation (Paroda et al. 1980). The productivity of the majority of the livestock, particularly cattle and sheep, is believed to be well below the potential which can be achieved with better nutrition (Kalla et al. 1980, Patnayak 1980). Over the last 100 years, for an area near Jodhpur, livestock mortalities have been high during a number of drought years; 90% of the cattle population died during migration in the 1868-69 drought; during the 1939 to 1940 drought, the mortality of cattle, buffalo, sheep and goats was 50%, 24%, 41% and 17% respectively (Bharara 1980).
It is significant that there has been an increase in the proportion of browsers (goats and camels - ACU $W^{0.75}$) in the livestock of W Rajasthan, from 13.9% in 1951 to 20% and 26.9% in 1961 and 1972 respectively (derived from Appendix 7A and 7B).

It would therefore seem that although a livelihood based on livestock production is precarious, a shift in the type of livestock owned may help in counteracting the effects of a reduction in the availability of pasture. Nevertheless, it has been estimated that during "drought" years, while crop production on rainfed land falls on average to less than 10% of the levels obtained in a good year, the production of milk and wool is still over 50% of that in a good year (CAZRI 1983).

7.5 Forest and fuel demand.

In W Rajasthan hardly 0.4% of the areas receiving an average of less than 250 mm rainfall per year are under "forest", while for areas with more than 300 mm, the forest area reaches 1.4%; however scattered trees occur over most areas (Mann et al. 1982). For T Rajasthan, the area under forest is said to be 9%. This is likely to be the area which is currently classified as forest and may bear no relation to the actual area under forest (Bentley 1984). Table 7.1 gives the fuel consumption figures for T Rajasthan (Kapoor 1984).

In the rural areas, the average consumption in T Rajasthan of crop residues and of dung as fuel has been estimated to be 95 kg (?W) and 158 kg (?W) per capita annually which would amount to 0.79 M (?W) tonnes and 1.32 M tonnes (?W) for W Rajasthan per year.
Table 7.1 Average annual consumption of some fuels in T Rajasthan (kg W.) per capita.

<table>
<thead>
<tr>
<th></th>
<th>Rural areas</th>
<th>Urban areas</th>
<th>State</th>
</tr>
</thead>
<tbody>
<tr>
<td>Charcoal</td>
<td>.01</td>
<td>21.05</td>
<td>3.84</td>
</tr>
<tr>
<td>Fuelwood</td>
<td>49.21</td>
<td>67.37</td>
<td>52.51</td>
</tr>
<tr>
<td>Twigs</td>
<td>159.10</td>
<td>77.33</td>
<td>144.23</td>
</tr>
</tbody>
</table>

No estimates of the annual wood production for forested lands, rangelands and croplands have been traced although there seems to be a general consensus that the annual harvest of tree biomass for fuel is considerably greater than that of the annual increment (e.g., Kapoor 1984, Mann et al. 1982 and Soni 1981). Certainly the fact that dung and agricultural residues are used when they have valuable alternative uses indicates that there is at least a serious localised shortage of fuelwood.
CHAPTER 8

Fodder Resources In W Rajasthan

The traditional sources of animal fodder are:

1) pasture from the rangelands;

2) crop residues;

3) fodder trees and shrubs (Fodder WPs).

8.1. Pastures.

8.1.1. Production.

The pastures of W Rajasthan have been classified according to their condition and quality. The rating has been based on points given according to the palatability of plants, botanical composition, density and dry weight yield of pasture plants and on the vigour and condition of browsed species (Shankarnarayan et al. 1965). However, the foliar production of fodder WPs has been excluded from production estimates of the rangelands (Bhimaya et al. 1969, Ghosh 1983). The estimated annual production and the year long "grazing capacity/carrying capacity"\(^1\) of pastures for a "normal" rainfall year are given in Table 8.1. for the different range conditions classes (Bhimaya et al. 1969). These estimates have been obtained from rangelands of the appropriate condition class which had been protected from grazing for a year (Ahuja 1975).

Annual pasture production can however be considerably higher, when

Note 1: The basis on which these were derived is unclear.
grazed or harvested at appropriate intervals, than the biomass of standing crop obtained at the end of the growing season in an area left ungrazed (eg. Thornton et al. 1971, Western 1982 for rangelands in E. Africa; Penning de Vries et al. 1982 for the Sahel). Although this is particularly so with perennial grasses it is not always the case (eg. with Andropogon gayanus Kunch var. tridentatus in Mali for a site with a mean P/EPT of 0.33, Cisse et al. 1980). No doubt the actual pasture productivity under various stocking rates within any given year will differ from those given in table 8.1, to different extents for

Table 8.1. Pasture production and grazing capacity of rangelands in different condition in W Rajasthan

<table>
<thead>
<tr>
<th>Condition class</th>
<th>Production 1 (tonne DM/ha)</th>
<th>Grazing Capacity 2 (ACU/ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Excellent</td>
<td>1.35</td>
<td>0.25 - 0.30</td>
</tr>
<tr>
<td>Good</td>
<td>0.90</td>
<td>0.20</td>
</tr>
<tr>
<td>Fair</td>
<td>0.68</td>
<td>0.17</td>
</tr>
<tr>
<td>Poor</td>
<td>0.45</td>
<td>0.13</td>
</tr>
<tr>
<td>Very Poor</td>
<td>0.18</td>
<td>0 - 0.06</td>
</tr>
</tbody>
</table>

Notes: 1 Derived from Bhimaya et al. (1969) data of air dry weights see Appendix 11)

2 Derived from Bhimaya et al. (1969) and Ahuja et al. (1975).

different condition classes, since the proportion of the biomass contributed by perennial grasses increases as the condition of the pasture improves (Bhimaya et al. 1969).

Studies under research station conditions in Jodhpur (mean P = 380
mm p.a.) on the perennial grasses *Lasiurus sindicus*, *Panicum antidotale*, *Cenchrus ciliaris* and *Cenchrus setigerus*, which occur mainly on the better condition rangelands, showed that over a three year study, the total annual yields were better with a 30 day cutting cycle than with shorter cutting cycles for years of sub-average precipitation (by 53% over a 20 day cycle in the case of *C. ciliaris* in a drought year and 20% over a 10 day cycle for *L. sindicus*). However in a "normal" rainfall year, *P. antidotale* and *C. ciliaris* yielded more with a 20 day cutting interval (24% more than the 30 day cycle in the case of *P. antidotale*) Dabadghao et al. (1973).

Deb Roy et al. (1975) showed in Pali (mean P = 420 mm p.a.) that the preferred perennial grass of wetter rangelands in good condition also had the highest yields per year with a 30 day cutting cycle (19% higher than for a 20 day cycle - a two year average).

Unfortunately these studies do not help to determine realistically the likely yields of pasture under heavy stocking density in a normal year. 80 to 90% of rangelands in W Rajasthan are classified as "poor" or "very poor" (Ahuja 1975) and therefore contain very few of the more productive and palatable perennials. Other perennial species make up less than 25% of the cover of the ground layer (Bhimaya et al. 1969). The remaining 10-20% of better rangelands are practically not grazed due to water scarcity (Ahuja 1975).

Other estimates of pasture production on open rangelands of W Rajasthan exist. Shankarnarayan et al. (1965) gave a value of 90.9 kg (?W)/ha for an area with mean P = 266 mm p.a. Ahuja et al. (1980) stated that an unprotected area and a protected area of Jaisalmer (a dry part of W Rajasthan) produced 61 kg and 760 kg/ha respectively.
However these authors do not give any indication of how these values were derived. Other estimates of productivity for village grazing lands have been given by Prajapati et al. (1975) but appear to be useless for this purpose because they are based on a measure of pasture biomass at the end of the growing season which is then multiplied by a factor to take into account the likely utilization of the pasture by livestock.

It seems that there are no accurate estimates of the actual pasture yields available to livestock. Ahuja (1975) proposed that the average forage yield per ha for a "normal" year from the arid rangelands of India was 0.4 tonnes - ie. 0.36 tonnes (DM) (other forage production figures in his paper referred to air dry weight).

Considering the evidence given so far, it is difficult to evaluate critically such a figure. If one assumes that a proportion of the "very poor" grazing lands can be attributed to the "Barren lands" of Appendix 6 and that one includes the area of rangelands which is little used due to water shortages, the figure of 0.36 tonnes DM/ha may be a realistic estimate of the average standing biomass in an area which has been protected for one growing season.

However the stocking densities found in W Rajasthan could result in yields being very different to those of standing biomass and would vary according to the resilience of the individual species - which may itself vary according to site and the specific climatic patterns encountered over a period of time. The few studies on the influence of the intensity of grazing on the yields of annuals from other regions with similar climates do not help to estimate the effect of the heavy grazing pressure in W Rajasthan. Variations in the timing and
intensity of cropping on annual grasses have different effects on yields. In an area of the soudano-sahelian zone of Mali (mean P = 561 mm p.a. mean P/EPT = 0.33), when the annual grasses are grazed during the growing season, there is both a reduction in yields (presumably because of a smaller root to shoot ratio than in perennials) and in the production in subsequent years because of reduced seeding rates (Cisse et al. 1980, Wilson 1982a). In the Charleville area of Queensland (mean P = 467 mm p.a. and P/EPT = 0.20), the calculated long term average herbage biomass production over the growing season on poor and medium condition (1% and 2.5% "ground storey basal area values" - a term undefined by the original authors), mulga pastures gave figures of 130 kg and 490 kg (?W)/ha (Christie et al. 1983).

Not all the above ground pasture biomass is utilised by livestock. It is assumed that the estimates given in table 8.1 refer to total biomass and not to that which is utilised. A proportion of the herbage biomass is unpalatable under any circumstances; Prajapati et al. 1975 gave a figure of c. 40 kg (ADM)/ha for a very heavily grazed village land. The percentage of the standing crop which is grazed and ingested varies according to the time of year, the pasture quality and the availabilty of alternative feed. For the sudanian and sahelian zones of Africa, Le Houerou et al. (1977) suggested that the proportion of the ground phytomass which can be consumed is of the order of 38-50% (60-80% during the 3 months of the rainy season and 30-40% during the dry season). This assumed that the livestock are transhumant and that the area which is grazed during the dry season is not the same as that grazed during the wet season). This is not the case in W Rajasthan.
where only some of the livestock migrates seasonally each year out of their monsoon grazing areas. The proportion of the remaining herbage which is grazed during the dry season depends on the factors limiting the dry matter intake (DMI) and this is discussed later.

Nevertheless, for the purpose of this study two approaches can now be taken:

1) the long term production average of 360 kg (DM) is maintained by allowing 70% utilization of the pasture (of the end of growing season standing biomass). Evidence that this utilization factor may be reasonable for W Rajasthan may be deduced from the fact that a 70% utilization factor for ranges of varying condition classes has generally resulted in improvements in production over the years (Mann _et al._ 1975); The recommendation which seems normally to be accepted as a "proper utilisation factor" for most range grasslands is however 50% (eg. Christie _et al._ 1983, IPAL 1982).

ii) one accepts that the pasture will degenerate further by not limiting the stocking density.

Under scenario i) (A1), livestock would therefore obtain 252 kg (DM) of herbage on an average rainfall year. Under scenario ii) (A2) one assumes that 80% of the pasture is utilized during the growing season and 40% of the remainder is used during the dry season. The amount consumed would be c. 317 kg (DM).

### 8.1.2 Grassland productivity and rainfall variation.

The effect of between year variations in the patterns and quantity of precipitation on the yields of "poor" and "very poor" pastures is
unknown. While they are assumed to be adversely affected by low rainfall (Ahuja et al. 1975), the quantitative evidence refers only to protected and better managed rangelands where the pasture biomass is greater and largely comprised of perennial grasses. Since the pasture biomass is so low at any one time on open rangelands, the yields may not be reduced relatively to the same extent as in perennials when compared to good rainfall years. Herlocker et al. (1980) have shown in the arid/semi-arid zone of northern Kenya, that "rainfall since the last dry period", "total rainy season rainfall" and "quarterly rainfall" were all significantly correlated with perennial grassland productivity; however none of these seasonal rainfall measures were significantly correlated to the annual production of annual grasslands, although there was broadly a decrease in productivity with lower rainfall. The influence of the previous year's total rainfall and of its distribution may be particularly significant for the production of annuals particularly through the effect on seeding rates. However since the rooting volume of annuals is lower than that of perennials, the degree of influence of variation in rainfall on their yield will depend on the size and distribution of the rain events (and therefore the depth and frequency of soil moisture recharge).

For a moderate drought year in W Rajasthan, the working assumption used here is of a 25% decrease over a "normal" year. Hence the pasture yield would be 270 kg (DM) with a 189 kg herbage consumption to allow for a sustainable level of pasture yield (scenario B1) and 238 kg for a maximum level of consumption (scenario B2).

For the year 1971, if the assumptions given are correct, the total consumable herbage from the rangelands of W Rajasthan which were
available for grazing was as shown in Table 8.2.

Table 8.2. Estimated average consumption of ground herbage in W Rajasthan according to various scenarios (see text for explanation).

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Area of rangeland (000 ha)</th>
<th>Consumption tonnes (DM)/ha</th>
<th>Total consumption (M tonnes DM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>8606</td>
<td>0.25</td>
<td>2.152</td>
</tr>
<tr>
<td>A2</td>
<td>8606</td>
<td>0.32</td>
<td>2.754</td>
</tr>
<tr>
<td>B1</td>
<td>8606</td>
<td>0.19</td>
<td>1.635</td>
</tr>
<tr>
<td>B2</td>
<td>8606</td>
<td>0.24</td>
<td>2.065</td>
</tr>
</tbody>
</table>

8.1.3. Pasture quality.

The quality of pastures varies according to their species composition and to the grazing regime. For the pasture conditions which prevail in W Rajasthan (ie. poor to very poor), the only values available are derived from a composite sample of grasses for a "poor" condition pasture. The CP levels were of the order of 6.5 to 6.8% (?W) during the growing period and of the order of 3% (?W) during the dry season (Mann et al. 1975). It is not clear if these values took into account the small proportion of legumes in the ground herbage. Their CP values are generally higher than in grasses both during the growing season and the dry season. CP values for *Indigofera cordifolia* ranged from 10.9 to 12.6% (?DM) at the end of September (Mann et al. 1975). It is not clear either if the values quoted are for the CP content of pasture plants which have been protected up to the time of sampling. This could considerably overestimate the feed value since it is well
known that livestock can select the better quality plant parts (Crowder et al. 1982).

It is assumed in this analysis that the average CP level of the available ground pasture biomass is 7% for the first month of growth, 6 and 5% for the remaining two months of monsoon respectively and 3% for the remaining 9 months.

The only value found for Phosphorus was from a composite grass sample from the Nagaur district of W Rajasthan. The content was 0.09% and 0.07% (?DM) for flowering and mature stages of grassland (Ahuja 1975). For the legume Indigofera cordifolia, a value of 0.18% (?DM) was obtained by Mathur et al. (1979) (no date of sampling given).

8.2. Crop residues and cultivated fodder.

The production of crop residues and cultivated fodder must be considered separately for irrigated and unirrigated areas since irrigated areas are not evenly distributed in W Rajasthan (see Table 9.1). The cultivation of fodder crops both on irrigated and unirrigated crop land has frequently been advocated (eg. CAZRI 1983, Paroda 1980) to improve the productivity of farms. Ramakrishna (1983) stated that rows of pearl millet grown for fodder and to provide shelter for other crops under dryland conditions at Jodhpur could result in increases of c. 30% in crop yields and in the production of 4 tonnes (FW) of fodder per ha. However reports suggest that the practice of intercropping forage crops with food crops on farms is almost non existent (Daulay 1980) and that of planting any area of dry cropland to forage crop monoculture very limited (eg. Paroda et al. 1980). The are few indications of the extent to which fodder crops are
planted under irrigation and it is assumed to be negligible (Roy et al. 1980). Hence the analysis of the fodder situation in W Rajasthan in 1971 assumes that any forage crop production was negligible.

8.2.1 Irrigated lands.

It is assumed that all the area which was cropped twice in 1971 (see Appendix 6) was irrigated land. No quantitative information was found specific to the irrigated areas of W Rajasthan concerning the areas planted to various crops or to their residue yields. However, by making certain assumptions and by relying on a number of sources which have discussed the subject in an incomplete way (see Appendix 8 and 9), it is possible to suggest that the likely production of agricultural residue from irrigated land in 1971 amounted to 0.533 M tonnes (DM) of good quality feed (CP and Phosphorus levels of 11 and 0.2% DM respectively) and 1.118 M tonnes (DM) of poor quality feed (CP and Phosphorus levels varying from 2.2 to 3.6% and 0.07 to 0.17 DM respectively) (see Appendix 9). The level of production would be unlikely to vary between a dry and a normal year unless water resources are diverted in a dry year from areas which are normally irrigated to areas which are normally rainfed. It has also been assumed that under irrigation the practice of sole cropping replaces traditional intercropping practices (Kanwar 1980). It is acknowledged that residue yields will vary considerably even within a crop according to variety, fertilizer regime, irrigation regime and weeding differences; however in the absence of more detailed evidence there is no alternative but to use these data as a working hypothesis. It is further assumed that because irrigated areas have a smaller proportion of common land from which fuel can be gathered, the total quantity of residue available for
animal feed was only 1.40 M tonnes (DM), 0.251 M tonnes (DM) having been used for fuel. The woody stem and roots of several crops make an excellent fuel (Das Gupta 1984).

8.2.2. Unirrigated lands.

It is assumed that unirrigated lands were only cropped once. The estimated production levels of residues from the crops grown on such land in 1971 are given in Appendix 9, with the various assumptions given in Appendix 8. Intercropping is generally practiced in the arid and semi-arid zones of India including W Rajasthan (Dauley 1980), and it is assumed that this has been taken into account by Mann et al. (1977c) and CAZRI (1983) in their figures concerning the areas under various crops, although they do not refer specifically to the the problems of interpreting census data when intercropping is practiced. The percentage area planted to legumes (56.8%) is considerably higher than that found in some traditional cropping systems in other parts of the world. Based on national statistics for Nigeria (1970-71) Okigbo et al. (1976) calculated that the area under a legume monoculture was 3.3% of the total area under monoculture and that the area under legumes in intercropped systems was 25.9%. For Uganda (1963-1964 data) they calculated that the area under legumes in monocultures was 11.9% and in mixed cropping systems 26.1%. The fact that other authors from W Rajasthan (eg. Jodha 1977) provided figures for areas under various crops which do not correspond with those provided by Mann et al. (1977c) and CAZRI (1983) suggests that some of the assumption in Appendix 8 and 9 could possibly be wrong. However care was taken to select the sources which seemed to make the most overall sense taking
also other factors into consideration (eg. total area cropped); Jodha's (1977) data on overall cropped area bears no relation to the total area which is given in Appendix 6. The importance of estimating correctly the proportion of land planted to legumes and to other crops lies in the fact that legume residues are of much better feed quality than those of other crops.

The estimated total production of crop residues for rainfed areas cropped in 1971 is 3.360 and 1.551 M tonnes (?DM) for a "normal" year and a "dry" year respectively. This excludes the small area (1.1%) planted to other crops for which no quantity or quality estimates can be made. It is assumed that the quantity of residues available as animal fodder amounted to 3.298 and 1.530 M tonnes in a normal and a dry year. This assumes that the residues of Sesamum and other crops were used for fuel and that the remainder of the fuel requirement from agricultural residues came from plant parts which cannot be used as feed (eg. roots and the bottom part of the stem, Das Gupta 1984).

The implication which an inaccurate estimate of residue yield may have on total fodder resources of W Rajasthan is acknowledged. Other sources of data on straw residue of some crops from W Rajasthan show much higher yields than those estimated in Appendix 9 (up to 9.6 tonnes ?W for pearl millet straw, Mann et al. 1977b, Mathur et al. 1980). However they have been disregarded because the results are from trials on research stations and from fertilized plots. The average grain yield on research station are known to differ from the average on-farm grain yields in the arid zones of India by up to a factor of 15 (Kanwar 1980). Further, CAZRI (1983) suggested that the "long term average" yield of fodder from crop residues of Pennisetum, Vigna aconitifolia
and *Vigna radiata* was 0.1 tonne (DM) per ha annually (see Appendix 9, note 4/). Evidence on crop residue yields from other parts of the world which receive more precipitation than W Rajasthan (see Appendix 10) indicate that the assumptions used here are not likely to be wrong by a large percentage. It does suggest however that Ahuja's (1975) figure of an average 1.25 tonnes (W) crop residue per ha available annually in the arid zone of India for livestock feeding (and which has been used since by several authors) is a considerable overestimate. Under the assumptions used here, during a normal year the total crop residue production available as animal feed amounted to 4.698 M tonnes (DM) and during a moderate drought year to 2.930 M tonnes (DM).

Using Ahuja's estimate, the production would reach 11.971 M tonnes (DM) his figure referred to gross area sown).

### 8.3. Fodder trees and shrubs.

A considerable number of tree and shrub species are browsed or lopped for fodder in W Rajasthan, particularly during the dry season. As mentioned earlier, Ghosh (1983) has suggested that the fodder WPs of W Rajasthan can meet the feed demand of the region on the basis of existing vegetation. A quantitative evaluation of their present role in animal nutrition and production requires an assessment of the actual quantities of foliage or pods seasonally consumed by different livestock from each fodder WP species in different parts of the area. Hence, an assessment is required of fodder availability and therefore of the foliar and pod production of trees and of their stocking densities under the harvesting regime imposed on them by livestock (browsing) or man (lopping).
However quantitative information is only available for a few species. Ganguli et al. (1964) listed the more important fodder WPs of India's N.W. arid regions and ranked them in terms of palatability by conducting trials with sheep, following the "cafeteria technique". Appendix 12 lists the species the foliage of which was rated of good and moderate palatability (the better 2 categories out of 4 listed) and provides information, where available, on the months when the species are in leaf and on the time of fruiting for the species which produce palatable fruits.

It is clear from Appendix 12 that published information concerning these species is incomplete. Further, the ranking of fodder WPs for palatability is likely to vary considerable for different types of livestock. It is known that some species are rated as palatable and even of good quality for one type of livestock but are unpalatable to other livestock. Nevertheless Appendix 12 does show that foliage from one species or another is available throughout the year.

Some species, eg. *Prosopis juliflora*, have foliage which is unpalatable or of poor palatability, yet their pods may be palatable and of considerable value to livestock (eg. Felker 1983, Robinson 1984 - see Annexe 3). Nevertheless the value of *P. juliflora*, from its pod production point of view, does not seem to be documented in India. Singh (1982) does not mention the species even though it is highly successful, is spreading in many areas and in some parts of W Rajasthan has virtually suppressed the growth of the indigenous species (Saxena 1977).

Quantitative information concerning fodder yields and quality is even scarcer. This analysis is therefore restricted to *Ailanthus*
excelsa, Albizia lebbek, Prosopis cineraria (Khejri) and Zizyphus nummularia (Bordi) for which some quantitative information exists from India and in particular W Rajasthan. It is an important indication that published information concerning phenology exists for only 3 species out of the 5 species noted to be the best in terms of palatability for sheep. Measured foliar or pod yields exist only for Khejri and Bordi.

8.3.1. Productivity.

Average yearly tree foliar or pod biomass figures are not the ideal measures of the contributions of WP fodder to animal nutrition. Apart from the need to take variations in quality into account (see Chapter 9), the important criterion is the amount of feed available at the time of selection by livestock or at the time of lopping both of which are site and time specific. The amount available varies according to previous demands made on the individual WPs for fodder and other products. Further aspects of productivity include the growth rate of WPs which influences the time it takes to reach a given size and level of foliar or pod production, and the longevity of the trees themselves, which also vary with environment and management. These points are discussed by species.

1) Albizia lebbek

No published yield data are available on this species. However it is interesting that in Jhansi (semi-arid zone of India), trees which had been lopped the previous year had not produced fruit in the subsequent year and retained their leaves considerably longer than trees which had not been lopped previously and which had produced pods
(Hughes 1984).

ii) *Ailanthus excelsa*

"Average sized" trees of *A. excelsa* are reported to yield 150 to 250 kg (dry matter) twice each year (Bhandari et al. 1972). If this is really so (see the following discussion on yields for species which have been better studied) this species would be particularly valuable.

iii) *Prosopis cineraria* (Khejri)

Khejri is a tree which varies in maximum height from 3 to 15 m depending on the site and precipitation (Saxena 1980). Its deep root system and ability to continue to be in leaf and transpire during the dry season suggest that it is - or at least can be - a phreatophyte (Lahiri 1980). It is generally lopped completely (except for the top branch) each year for dry season fodder. Lopping occurs between October and January particularly on private cropland.

The evidence concerning the yield of fully lopped Khejri trees seems to be very inconsistent. Figs. 8.1, A,B give the results (or assumed results) of yields from lopping trials. Fig. 8.2 refers to measurements of leaf biomass from felled trees which may never have had their canopy lopped, in which case the data are of little relevance to the likely yields from lopped trees. Appendix 13 lists the estimates made by various authors concerning foliar yields and the results of lopping trials and describes the investigations from which Figs. 8.1 and 8.2 are derived. (It must be emphasized that the data given in Fig 8.1A are based on different interpretations of the original data than that of the investigators).

The estimates which are generally quoted and accepted (e.g. Tejwani 1983) give yield values ranging from 20 to 60 kg (dry matter) of foliage
Average annual foliage yield of *Prosopis cineraria* (FW) from trees of different dbh and under varying lopping cycles.

(The data in fig. A concerning trees lopped every 4 years are derived from a different interpretation of the original results than that of the authors – see Appendix A.13.6).
Fig. 8.2 Wood and foliage biomass of *P. cineraria* trees (from Mann et al. 1983)
annually per tree. Yet 4 lopping trials show very different results. Fig. 8.1.A shows yield increases getting greater with increasing dbh class from 20 cm to 40 cm. The average annual yield from December lopped trees with a dbh of 35 to 40 cm was 4.7 kg (?DM). Fig. 8.1.B shows yield increases getting smaller with increases in dbh from 10 to 30 cm (the trees were also lopped in December); the annual yield from trees with a dbh of 25 to 30 cm was 1.6 kg (?DM) (compared to 3.1 kg for the same dbh class in Fig. 8.1.A). The lopping trial quoted by Mann et al. (1984) (Appendix 13.9) gave an average annual yield of 57.3 kg (?W) per tree (the average size of the trees and the season of lopping were not specified). Appendix 13.10 and table A.13.3 give the results of a lopping trial with small trees in which November lopped trees yielded an average of 0.41 kg (DM) per tree (the average dbh of 4 trees was 7.47 cm) over 3 years (Sharma et al. 1981).

Part of these discrepancies in yields could have arisen from the fact that some authors may possibly have included twigs in their estimates and others only leaves. Further, the results of lopping trials which are initiated with trees which have previously not been lopped or which have had a few years without lopping should exclude at least the first year's results from the means; the first year's yield data would be likely to be considerably higher than which had previously been lopped at least for trees up to a certain dbh size, because they possess a fully developed canopy (see Appendix 13.9 and 13.10). It is also possible that Mann et al's (1984) yield data referred to fresh weight. However even if this was so, the average annual dry weight (?DM) yield for the last 3 years of their trial would have been 22.5 kg (see Appendix 13.6 concerning the FW to ?DM
conversion factor and Appendix 13.9). There is unfortunately no
evidence to confirm that such explanations concerning discrepancies are
applicable to the studies which have been reviewed in Appendix 13.
Further the discrepancies still seem quite large even if one takes into
account the latter two explanations, although the inclusion of twigs
with foliar biomass could no doubt account for the discrepancies.

Since the results of lopping trials on Khejri trees of more than
25 cm dbh and the estimates of their foliar yields have been found to
vary by a factor of more than 35 (1.6 kg ?DM and 60 kg ?DM per tree —
see Appendix 13.8), it was thought relevant to see if data on foliar
yield and biomass from other dry zone legume trees and which occur in
other parts of the world and have small leaves could indicate the range
of values which could be expected to be correct for Khejri. Appendix
18 gives the results of such a review but these do not help to
determine the yield levels which are likely to be more realistic since
the foliar biomass figures ranged for 1.6 kg (?DM) to over 25 kg (DM)
per tree for Acacia tortilis (in Bourkina Fasso) and Acacia aneura
(in S.W. Queensland) respectively (both sets of figures are for trees
with stem diameters of 30 cm either at base or at 30 cm above ground).
The yields of Acacia seyal were up to twice as large for similar
diameter classes in Mali as in Bourkina Fasso (Appendix 18.1 and 18.3),
although differences in site and in climatic conditions during the
years of sampling may have been at least partly responsible. The
figures available for Prosopis tamarugo in Chile are unusually high
but there are doubts concerning the relationships shown in Fig. A.18.4.
It must be emphasized that it is possible that none of the data
provided in Appendix 18 refer to trees which had either been substantially browsed or lopped prior to measurements being made on their foliar biomass.

If one's objectives are to obtain maximum cumulative leaf production from trees over a given rotation, the rate of growth is particularly important for a number of reasons.

The faster the roots grow and reach the water table, on sites where there is a water table, the less the growth rate and foliage production will be influenced by variations in annual rainfall.

On sites where it is desirable to graze livestock and to have the canopy out of their reach so as to be able to control the time when tree foliage is provided, a faster growth rate is desirable. No published information on browsing height is available from W Rajasthan but studies in N Kenya suggest a 3 m upper limit for camels (IPAL 1982); with smaller trees, foliage in the centre of the canopy becomes inaccessible to camels when the crown has a diameter of 3 m.

Observations in the Sahel suggest a 2 m upper limit for foliage accessible to cattle, goats and sheep (Hiernaux 1980, Piot et al. 1980) (although the branching structure of some tree species enables goats to climb into the tree, thereby giving them access to foliage beyond 2 m above ground).

A fast growth rate in terms of dbh is important since dbh is generally positively correlated with foliar biomass and yield (eg. see Fig. 8.1.A. and B, further evidence is given for 6 fodder WPs in the sahelian zone of Bourkina Fasso, Piot et al. 1980) and pod yields (Cisse 1983). Unfortunately there do not seem to be any published records of dbh increments with age for Khejri. Fig. 8.3 illustrates a
Fig. 8.3 Possible relationship between age and dbh of *P. cineraria* on good sites in W.Rajasthan (derived from two separate relationships given in Appendix 17).

Note: It must be emphasized that if this relationship is realistic it must be the lower section of a sigmoid curve.
possible relationship between age and dbh of Khejri derived from two separate sets of data: dbh to height and age to height (from different tree populations) (see Appendix 17).

The factors which may influence the rate of growth and which are discussed in this section include the inherent site characteristics and the lopping/browsing regimes of the trees. Site management factors (eg. site preparation, intercropping) are discussed in Chapter 9.

Growth rates of Khejri are likely to vary according to site characteristics although no data seem to be published on the subject. However the fact that the maximum height of Khejri varies from 4 m (on interdunal plains receiving 150-250 mm rainfall) to 15 m on young alluvial plains with a good water potential (Saxena 1980) further suggests that the growth rate of trees in the 350 mm to 450 mm rainfall zone is twice as great as in areas of shallow soils and low rainfall (100 to 200 mm p.a) - taking 10 to 20 years respectively to become "fully grown trees".

The relevant factors in terms of browsing/lopping regime are the intensity, the frequency and the seasonality of the harvest.

Intensity

Bhimaya et al. (1964) referred to recommendations that the upper 1/3 of the canopy of trees should be left intact if future foliar production was not to be jeopardized (see also discussion in Annexe 3). However two lopping studies (Bhimaya et al. 1964, Mann et al. 1984) have shown that over 4 year periods, trees lopped completely (except for the leading central shoot) each year yielded more than those which only had 2/3 or 1/3 of the canopy lopped. Mann et al's. study gave no indication that after 4 years yields of completely lopped
trees were decreasing.

The only data concerning the influence of lopping intensity on tree growth are provided by Bhimaya et al. (1964) who stated that complete lopping leads to statistically greater increases in height and stem girth compared to partial or no lopping. However since the initial height and girth of the trees from the 4 treatments were not provided, it cannot be excluded that the size parameters differed significantly prior to the trial. Table 8.3 (see also sub-section on the effect of timing of harvest in this section) shows that for the young trees in Sharma et al.'s (1981) lopping trial, two year increments in dbh for two groups of completely lopped trees differed little from increments which would be expected from the possible age to dbh relationship represented in Fig 8.3 (unfortunately they did not include a control group of unlopped trees). Data from the Sahel shows that the nature of the response and its magnitude differ in various species with different stripping regimes (including stripping intensity) (see Annex 3). Considering that it is generally accepted that the ratio of above to below ground biomass is fairly constant for any given species of a particular size and given similar environmental conditions (ITE in press), the results showing that complete lopping has a stimulatory effect on tree growth are surprising. It has been suggested that there is evidence that the removal of old leaves and twigs may have a stimulatory effect on growth of the remaining younger shoots (Cannell 1983). However such studies referred to only partial pruning of a selective nature, and the stimulated growth is likely to have been preferentially partitioned to specific components of the above ground biomass. It is also possible that since Khejri trees are
likely to have a large underground biomass, the removal of a small proportion of the above ground biomass would have little effect on the ratio of below to above ground biomass. Nevertheless common sense would suggest that the annual removal of the whole of the foliar biomass would tend to result in a lower foliar production as the inherent below to above ground biomass ratio becomes re-established each year. Since most traditional lopping is done just prior to the start of leaf fall, it is likely to have the least negative influence on growth and subsequent yields (this point is discussed below).

Farmers in W Rajasthan usually lop Khejri trees completely except for the central leading shoot (Saxena 1980). It may be significant that the traditional way of harvesting leaves in some areas of W Rajasthan where the density of trees is naturally low, is by wiping the branches with leather gloves resulting in the removal of approximately 75% of leaves and in no damage to twigs (Purohit et al. 1980). This practice should result in a reduced imbalance of the above ground to below ground biomass ratios. However no work has been done on the relative merits of tree lopping versus branch wiping.

**Timing of the harvest**

The lopping trials which have been carried out have lopped the trees in December. Usually the local practice of recurrent lopping starts in the middle of November and continues until the middle of January - i.e. just before natural leaf-fall. However in the case of trees growing in irrigated fields where a dry season crop is planted, the lopping is completed by the end of October (Saxena 1980). Observations have been made that Khejri trees which are not privately owned are lopped earlier than privately owned trees in the same area.
During years of feed shortage, newly sprouted twigs and leaves are also harvested (Saxena 1980). Mann et al. (1983) stated that 10 to 33% of the May-June regrowth is also generally lopped in croplands both for animal feed during the season of feed scarcity and to reduce shade on growing crops.

The effect of complete lopping in different seasons on both foliar yields and on tree growth has been investigated by Sharma et al. (1981) on small Khejri trees (see Appendix 13.10 and table A.13.3). Unfortunately their investigation has little value in suggesting the effect which the season of lopping may have on yields since the various treatments included groups of trees the mean size of which were considerably different. Only 3 years' data on yields were collected and since the yield of foliage is said to be considerably influenced by the previous year's precipitation (this must be particularly so with small trees), it is difficult to evaluate from their data the influence of season of lopping on subsequent foliar yields. Longer term studies would be desirable. Considering that the February lopped trees were somewhat smaller than the November lopped trees, it is surprising that their mean foliar yield was only 29% lower (see table A.13.3). However it could be that the February yield value included old leaves which had not yet fallen (see Appendix 12). The results from the wood yield data also suggest that February lopped trees have enough regrowth period after lopping to approach the yield levels which would be expected in November lopped trees.

Taking into account dbh increments over the trial period rather than final dbh as the authors did, a different conclusion emerges
concerning the influence of the season of lopping on tree growth; they compared the mean height and dbh values over 3 years of study but omitted to take into account the considerable difference in initial size (dbh and height) between the treatment groups. February lopping does not have the detrimental effect on the tree growth which the authors claimed. Although no statistical analysis can be made to ascertain the significance of the differences in growth (no individual tree data were provided), the results suggest that May and to a lesser extent August lopped trees, grow less than those harvested in February and November. If this is actually so, it may be because May lopped trees do not have enough regrowth time before leaf fall to enable enough photosynthate to be produced for height and dbh growth. August lopped trees, on the other hand, may already have produced enough photosynthate to be translocated back for stem growth.

Table 8.3 shows that over 2 years, the mean dbh increments of February and November lopped trees do not differ markedly from the increment which would be expected from unlopped trees if the relationship between age and dbh shown in Fig. 8.3 is realistic.

Table 8.3 dbh increment (cm) of Khejri lopped in February and November (derived from Sharma et al. 1981) and expected increment (cm) for unlopped trees (derived from Fig. 8.3).

<table>
<thead>
<tr>
<th></th>
<th>February lopped</th>
<th>November lopped</th>
</tr>
</thead>
<tbody>
<tr>
<td>2nd year dbh</td>
<td>5.13</td>
<td>7.47</td>
</tr>
<tr>
<td>Measured</td>
<td>Expected</td>
<td>Measured</td>
</tr>
<tr>
<td>4th year dbh</td>
<td>8.70</td>
<td>8.40</td>
</tr>
</tbody>
</table>
Frequency of harvest

Ganguli et al. (1964) mentioned that some species require 2 or 3 growing seasons' rest from lopping to maintain their productivity. The above discussion concerning Sharma et al's (1981) data, Bhimaya et al's (1964) data (Appendix 13.6) and Srivastava's (1978) data indicate however that Khejri does not seem to require years with no lopping. However the studies referred to in Fig. 8.1.A and 8.1.B were carried out over 4 and 3 years respectively and it could therefore be that trials carried out over a longer period would come out with different results (see Annexe 3).

However, Bhimaya et al. (1964) seemed to compare the yield from trees which had been rested for 4 years with the annual yield of trees lopped annually and concluded that some years of rest were required for sustained maximum forage yields. Such a comparison is unreasonable and therefore their conclusion untenable. More recent publications on Khejri (eg. Leakey et al. 1980, Saxena 1980, Singh 1982 and Tejwani 1983) have, it appears, referred uncritically to Bhimaya et al's (1964) conclusions possibly resulting in incorrect recommendations concerning lopping strategy.

Saxena (1980) suggested that "ruthless" and irregular lopping affected the normal growth of trees and that mortality may result. No evidence has been found to substantiate this suggestion.

When the trees are young repeated browsing by goats and other livestock is said to be detrimental to Khejri (Singh 982), protection of young plants against browsing until the trees are out of reach of livestock is therefore essential.
The available evidence (assuming that the interpretation which has been made here concerning Bhimaya et al.'s (1964) data is correct) suggests that the traditional practice of recurrent complete lopping once a year during December and January does not have a detrimental influence on subsequent foliage yields. Clearly the data provided by some of the trials to date should be reanalysed and longer term lopping trials undertaken to confirm the suggestions. In this analysis it is assumed that foliar yields are sustainable under a recurrent annual lopping regime carried out in November to January. Since no data are available concerning the yields of foliage and shoots from a second lopping during the months of greatest shortage (May-June), for this analysis it is assumed that the yield from a tree lopped each winter is the same as the cumulative yield from a tree lopped in winter and lopped again after leaf emergence. It is however acknowledged that this assumption is open to question and may in fact be conservative in the case of trees lopped early enough after sprouting (see discussion above).

The age at which first lopping of Khejri should theoretically start (see Appendix 13) to get maximum cumulative foliar production over a given number of years from a tree depends on the extent to which tree growth is reduced by lopping; this could vary according to time of lopping, age or size of the tree and site characteristics. The evidence on this point is unsatisfactory, although what there is suggests that winter and spring lopping may not be detrimental, browsing before the leading shoot is out of reach of livestock is likely to be detrimental. Since no published data seems to exist relating dbh to age (data exists relating height to age in trials), it
is impossible to know if statements made in Appendix 13 (2,3) - ie. that lopping can start at year 8 to 10 - are correct. If Mann et al's (1983) data (Fig. 8.2) are correct, the best strategy would appear to be to let the trees reach a dbh of 20 cm as fast as possible. Srivastava (1978 - Fig 8.1.B) suggested that only trees with a dbh of more than 15 cm should be lopped.

It has been impossible to develop from the various sources available a model of the likely foliar yields for different dbh categories during the life of Khejri on different sites and given different harvesting regimes. An estimate of the average likely yield over the harvestable life span of Khejri is however necessary.

It is assumed that harvesting starts when the trees have a dbh of 10 cm and that the average productive life of trees which are lopped annually is 150 years (Tejwani 1983 suggested, on what basis it is not clear, that trees "may go on producing for up to 200 years", other sources suggest that lopping sometimes leads to rot setting in and at times to tree mortality).

It is assumed that on better sites with an average annual precipitation of more than 300 mm, it takes an average of 10 years to reach a dbh of 10 cm (from Fig 8.3) and 20 years on poorer sites and sites with a precipitation level of less than 300 mm.

The extent to which leaf yields vary with annual fluctuations in precipitation is not clear and presumably varies with other site factors (eg. depth of the water table, soil depth and structure, soil moisture retention capacity, extent of run off onto or off the site etc.). Saxena (1980) suggested that during drought years the foliar yields are reduced. Sharma et al. (1981) suggested that foliar yields
were more influenced by the previous year's precipitation. For this analysis it is assumed that the yields are constant.

It is likely that pod production is minimal in lopped trees (Muthana 1980 - see Appendix 13.4). Hence the suggestion that a fully grown tree produces 25 to 30 kg of leaves (ADM) at lopping and 5 kg of pods each year (Mann 1980) is likely to be unreasonable. Pod production is not taken into account in this analysis in terms of its contribution to livestock feed.

Because of the impossibility of deriving one reasonable figure from the various sources quoted in Appendix 13 for an average yield of foliage from an average "mature sized" tree, this analysis assumes two possible levels of production for better and poorer sites. Table 8.4 summarizes the average yields from 2 lopping trials on good sites for different dbh classes. Sharma et al's. (1981) results gave a mean yield of 0.45 kg (DM) for trees with a dbh of 10.25 cm.

Table 8.4. Average foliar yield (kg ?DM/tree) of Khejri obtained for different dbh classes by Bhimaya et al. (1964) and Srivastava (1978).

<table>
<thead>
<tr>
<th>Dbh class (cm)</th>
<th>10-20</th>
<th>20-30</th>
<th>30-40</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bhimaya et al.</td>
<td>2.95</td>
<td>4.07</td>
<td></td>
</tr>
<tr>
<td>Srivastava</td>
<td>0.99</td>
<td>1.47</td>
<td></td>
</tr>
</tbody>
</table>

For the purposes of this analysis it is assumed that the lower estimate of foliar yield for better sites is as shown in Table 8.5 for different diameter classes (derived from a figure lying between Bhimaya
et al's and Srivastava's data). The table also gives the estimated number of years during which trees are in each dbh class, and the calculated yield over the productive life of the trees. The average annual foliar yield of Khejri over the productive life would therefore be 4.46 kg (DM)/tree. It is therefore assumed that on better sites the lower estimate for an average annual yield from year 10 to year 150 would be 4.5 kg (DM)/tree. For poor sites and sites with a precipitation of less than 300 mm, it is difficult to estimate realistically an equivalent average yield; however considering that trees are considerably smaller and may seldom reach a dbh of 40 cm (Saxena 1980), it is thought unlikely that the average annual yield would be greater than 2.5 kg (DM)/tree from year 20 to 150.

Table 8.5. Estimated yields (kg DM/tree) of Khejri trees in different dbh classes, estimated number of years during which trees are in each dbh category and estimated cumulated yields over the productive life of a tree (for good sites).

<table>
<thead>
<tr>
<th>dbh class (cm)</th>
<th>10-20</th>
<th>20-30</th>
<th>30-40</th>
<th>40+</th>
<th>total</th>
</tr>
</thead>
<tbody>
<tr>
<td>yield (kg)</td>
<td>1.5</td>
<td>2.20</td>
<td>3.00</td>
<td>5</td>
<td>7.50</td>
</tr>
<tr>
<td>years</td>
<td>5</td>
<td>10</td>
<td>15</td>
<td>100</td>
<td>140</td>
</tr>
<tr>
<td>total (kg)</td>
<td>7.50</td>
<td>22</td>
<td>45</td>
<td>550</td>
<td>624.5</td>
</tr>
</tbody>
</table>
Since 3 out of 4 lopping trials obtained yields which were of the same order of magnitude (Bhimaya et al. 1964, Sharma et al. 1981 and Srivastava 1978) it is felt that the estimates of 4.5 and 2.5 kg (DM)/tree for better and poorer sites are likely to be the more realistic estimates. However the possibility that Mann et al's (1984) results (Appendix 13.9) and various other estimates giving yields of 20 to 60 kg (?DM)/tree are correct cannot be completely dismissed. Hence a second higher average estimate of 20 kg and 30 kg (DM)/tree is also assumed for the productive life of trees on poor and better sites.

iv  Zizyphus nummularia  (Bordi)

This is a thorny shrub of 1-2 m height (Saxena 1981) which reaches a height of 4-5 m when not browsed or lopped (Muthana 1981).

The bush is harvested during November/December once the crops have been harvested and before leaf fall (Purohit et al. 1981). The plants are cut to ground level and heaped up until the leaves can easily be separated from the bushwood. The dry leaves are stored for the months of feed scarcity. On grazing lands, the young shoots are heavily browsed during the summer months by all livestock as they are generally within easy reach (Bohra et al. 1981, Saxena 1981a). Plants are harvested again in April/May in years of fodder shortage (Purohit et al. 1981).

Appendix 14 lists the various estimates which have been published on the leaf fodder biomass and yields of Bordi, as well as the results from the few harvesting trials which have been carried out. It would appear that estimates of more than one kg per bush are likely to refer to bushes which have been protected for a number of years, thereby enabling the canopy to develop. Such estimates are likely to be
irrelevant in terms of productivity from annually harvested bushes. Some of the other evidence is of questionable relevance since it is unknown if the shrubs had been protected for any period prior to the measurements being made. Appendix 14.3 shows that the plants which Shankar (1981) was measuring differed greatly in the ratio of bushwood to foliage; this suggests considerable differences in bush size and previous management rather than influences due only to land use and other site differences.

The most relevant data available are those provided by Saxena et al. (1981) (Appendix 14.6 and Table A.14) which refer to bushes which were coppiced annually over a period of 5 years during different seasons. From their results it seems clear that the traditional period of harvesting (November/December) results in the greatest recurrent foliage yields. Complete harvesting during the period between shoot sprouting and the monsoon leads to production levels which are below the production potential of the species (80% lower for summer lopped compared to winter lopped bushes).

The effect of partial removal of leaves and twigs compared to whole plant harvesting does not seem to have been investigated. While the traditional form of harvesting involves the cutting of the bush at ground level, various browsing intensities are likely to result in the removal of different proportions of bushes with probably different effects on subsequent bush production. The effect of the frequency of harvesting on yields does not seem to have been investigated either.

The influence of site equality and land use type on yield is not well documented. Shankar's (1981) data (Appendix 14.3) cannot reliably be used since the management history during the year of harvest and the
season of harvest are not specified. However it would be reasonable to suppose that the potential productivity on poorer and/or shallower soils (eg. grazing lands) would be lower than the yields obtained by Saxena et al. (1981) on deep soils in Johpur (a site more characteristic of croplands).

Once well established (at 3 years of age, Bohra et al. 1981) it is assumed that the productive life of a bush, if harvested once a year during the winter, would be approximately 50 years.

It appears, however, that more frequent harvesting results in lower productivity. Grazing trials with sheep and goats at 3 different year long stocking densities varying from 3 to 6 animals per ha on "good" quality pastures (at Pali, mean P = 607 mm p.a. for the 3 years of study) showed that the percentage cover of Bordi was reduced over successive years. The percentage canopy cover decreased at the medium stocking densities (4 animals/ha) from 20% to 16.2 and 3.8% respectively in sheep and goat paddocks (the crown measurements at the end of the trial were made in December after the monsoon) (Harsh et al. 1981).

The yields of foliage seem to vary considerably according to the years' total precipitation (Saxena et al. 1981).

For this analysis it is assumed that on a good site, the yields of Bordi bushes which are harvested annually are 0.18 kg (DM) for a mean rainfall year of 400 mm with a reduction or an increase in yield in the same proportion as the variation in precipitation around the mean up to a 50% variation (ie. 0.09 kg DM in a 200 mm rainfall year and 0.27 kg DM in a 600 mm rainfall year) (derived from Saxena et al. 1981 - Appendix 14.6). Lower yields would be expected on poorer sites.
(shallower soils etc.) but no appropriate information seems to be available to give an indication of the extent to which the yields may be reduced.

8.3.2. Fodder WP stocking densities

Any attempt to estimate the amount of foliage available from WPs requires, apart from data on yields for trees in different dbh classes, information on the stocking density of WPs in different areas of W Rajasthan. Both to estimate yields and to evaluate the status of the populations of each WP species, information on the dbh and/or age structure of the populations is required.

Although vegetation surveys have been undertaken for more than 20 years in W Rajasthan, particularly by CAZRI scientists, most of the information which has been published is not detailed enough to determine stocking densities of the relevant fodder WPs. Meher-Homji (1977) and Saxena (1977) have described the major vegetation types of W Rajasthan and the climatic and soil conditions which determine species composition. Meher-Homji gave a range of stand densities only for Khejri but since his descriptions refer primarily to "natural vegetation unaffected by human interference", the information is irrelevant to the present analysis since as he stated "only traces of it's (the natural vegetation) are left in protected places". Saxena (1977) gave ranges in terms of tree height, percentage canopy cover, dbh classes, stems per ha and standing biomass but for the woody vegetation as a whole and not by species. He provided information on the ranges of plants per ha and on plant height for a few species such as Khejri, A. senegal and Capparis decidua but no data on the dbh
structure of the stands. Again the majority of the information seems to refer to the few remaining areas of climax vegetation which can be found in W Rajasthan. The few descriptions of degraded sites state that the tree stocking densities are much lower but surprisingly none of the ranges given refer to areas with zero trees.

If one was only interested in trying to predict what the climax vegetation would be in various parts of W Rajasthan, including potential tree densities and standing biomass one could rely on the aforementioned vegetation surveys combined with the detailed inventories of the major "land resource units"/"soil associations" which have been identified for W Rajasthan (Gupta 1972, Mann et al. 1977c) with which vegetation types can be correlated. However such detailed inventories have so far only been completed for Jodhpur and Nagaur districts (Shankarnarayan 1975, 1980) which cover 49,183 km² or 19% of W Rajasthan.

It is again only for Khejri and Bordi that some detailed information is available.

i) Prosopis cineraria

Saxena (1980) stated that the Khejri tree is well distributed throughout the plains of W Rajasthan on sandy loams, loam and sandy clay soils (which often have a hard pan at depths varying from 50–150 cm). Fig. 8.4 shows a map produced by Shankar (1980) which he suggested showed the density of Khejri in the different areas of W Rajasthan. The data from which he appears to base his map of Khejri tree densities are shown in Tables A. 16 (a–e) (Appendix 16). As discussed in Appendix 16(1), because of dubious sampling methods and a biased selection of sample plot data, Fig. 8.4 does not show the actual
Fig. 8.4 "Density of Khejri" in W. Rajasthan (from Shankar 1981).
density of Khejri trees in the different parts of W Rajasthan but probably at best the potential density; In reality large areas of W Rajasthan have very few trees indeed (personal observation, Hughes 1984).

No detailed information seems to have been published on the age or dbh structure and status of any Khejri populations (Muthana 1983). Saxena (1980) stated that during the ecological surveys of Nagaur and Jodhpur districts, several stands of almost uniform dbh were recorded. He suggested that this indicated the occurrence of favourable years of rainfall enabling regeneration to take place. Unfortunately the original data have not been published so it is not possible to attempt to elucidate the conditions under which regeneration may have taken place. Although good rainfall years would clearly be important for quick early growth which is likely to be essential for effective establishment, other factors may also be important. The conditions which lead to a good pod production year are important and these may include both climatic conditions and tree management factors; the latter are known to vary in any particular year with the fodder supply and demand situation. This in itself varies considerably according to climatic conditions which have prevailed over the preceding years and which have affected livestock population numbers and composition, and their migration patterns. Bille (1980) has noted that regeneration of some fodder tree species in the Sahel is highly irregular, possibly requiring a number of conditions which rarely coincide.

In parts of W Rajasthan the older people claim that over the last 30 years there has been a reduction of 60 to 65% in the overall tree and shrub population (Malhotra 1984). The results of questionnaire
surveys in Nagaur district suggest that the decrease in overall shrub and tree numbers in pastoral, rainfed and irrigated areas had been of the order of 60, 40 and 25% respectively (Malhotra et al. 1980). However respondents also claimed in Nagaur district that the numbers of Khejri trees had increased substantially since the change of land ownership structure prior to which rulers used to cut the trees indiscriminately. It is impossible to evaluate the results of such questionnaires without knowing more about the questionnaire design and approach.

Saxena (1977) suggested that the density of Khejri increases in enclosures protected from grazing Purohit et al. (1980) and Singh (1982) suggested that browsers have a detrimental impact on its regeneration and survival. It would seem quite plausible that due to the increase in livestock densities on the grazing lands, the percentage of Khejri plants which grow into trees may be considerably lower than in the past and one may well be witnessing relic populations of Khejri on non private land (personnal observation, Hughes 1984).

On private cultivated lands, Khejri tree densities vary according to the precipitation, soil depth, presence of a water table and must also vary with the attitude of farmers to trees and the degree to which they are prepared to encourage and protect their growth. The following give the various estimates which have been published on Khejri densities for farmers fields in W Rajasthan:

a) 62 to 87 trees per ha (the density which is traditionally preferred and maintained in arid Rajasthan, Malhotra 1981);

b) 100 to 150 trees per ha (East of Jodhpur, Muthana 1983);
c) 20 to 40 trees per ha (flat alluvial plains, soils 100-150 cm deep, mean P = 350-450 mm p.a., Mann et al. 1980);

d) 40 to 120 trees per ha (2 to 4 m deep older sandy alluvial plains of Nagaur and Ganganagar districts, Mann et al. 1980);

e) 150 to 200 trees per ha (optimum density on alluvial plains of Sikar, Churu and Nagaur districts (Mann et al. 1980a);

f) normally 40 to 60 trees are maintained per ha by farmers (Paroda et al. 1981).

Malhotra (1981) however stated that Khejri densities were dropping in areas where field cultivation is mechanized by tractors.

ii) Zizyphus nummularia

Saxena (1981a) stated that Bordi is the most commonly occurring shrub species in the arid and semi-arid areas of the Indian desert and that it occurs over vast areas of the zone receiving a mean annual rainfall of 150 to 250 mm. It apparently does not occur in saline areas or on sand dunes (which themselves however occupy large areas of W Rajasthan).

In an attempt to obtain relevant data concerning Bordi shrub densities in various habitats and types of land use, the same problem has arisen as for Khejri densities, since the data which are available have resulted from the same surveys on arid shrublands (see previous section and Appendix 16). Appendix 19 gives Shankar's (1980) tables of Bordi densities on various sites. The fact that not a single sample site had no Bordi (except for one uncertain one on river beds - which was not taken into account to calculate the mean) leads one to doubt the relevance of the data in terms of average Bordi densities for the various areas of W Rajasthan. It is likely that there was the same
bias in the sampling strategy as that described for Khejri in Appendix 16. As Shankar (1981) himself stated, the observed density of Bordi in any habitat is largely governed by biotic factors. The effect of various stocking densities of goats and sheep on Bordi has already been described above (section 8.3.1/Bordi, Harsh et al. 1981). The survey omitted, as for Khejri, to sample cultivated fields. Saxena (1981a) also stated that in hilly areas which had 80 to 350 Bordi plants per ha in protected zones, unprotected zones had 10 to 50 bushes per ha.

Farmers have traditionally favoured the presence of Bordi on their fields. Appendix 15 referred to 3 cultivated fields in the Jodhpur district where Bordi bushes had been counted (550, 2820 and 1660 bushes per ha, Shankar 1981). Saxena (1981b) stated that on cultivated fields with a well defined hard pan at 100 to 150 cm depth, the density ranged from 250 to 500 bushes per ha, but that in fields cultivated by tractors, the bush density had been considerably reduced. Malhotra (1981) stated that the traditional density of Bordi in cultivated areas is 250 to 300 plants per ha. However the recent introduction of tractor ploughing has reduced Bordi densities in many areas to 60 to 75 plants per ha.

8.3.3. Fodder chemical composition

One of the attractive attributes of the better fodder WPs is their apparently high feed quality as indicated particularly by the high CP values of their leaves. Ahuja (1977) stated that their nutritious leaves and pods are an important source of protein and minerals which are particularly valuable during the dry and lean period when other
forage is of low quality, and they therefore increase livestock productivity. Partly for this reason, their introduction in grazing lands has been recommended (e.g. Paroda et al. 1980). Appendix 23 gives the percentage dry matter, CP, calcium and phosphorus values for 7 of the better fodder WP species of W Rajasthan. The CP values are considerably higher than those given in section 8.1.3. and in Appendix 9 for pasture plants and crop residues respectively and range from about 10% to 20%. The high moisture content is also said to be particularly valuable since during the summer months a considerable proportion of the water requirement of livestock can be met by fresh WP foliage (Ghosh et al. 1981). Bohra et al. (1981) suggested that about 30% of the total daily water requirement of sheep and goats can be met by Bordi foliage alone. The availability of such forage during the dry season should therefore extend the grazing distance away from sources of water and therefore extend considerably the total area available for grazing and reduce grazing pressure. Given that the chemical composition of foliage may vary between seasons, it is surprising that only 25% of the investigations quoted in Appendix 23 have recorded the season during which the leaves were harvested. Further only two of the studies out of the 21 which are referred to (by Gupta et al. 1974b on Khejri and Sharma et al. 1966 on Albizia lebbek) described the foliage sampling procedure. Variations in sampling season and position of the leaf in the canopy may be reasons for the considerable within species differences which appear to occur according to the figures given in Appendix 23 in the chemical composition of foliage (see also Annex III).

No analyses of the chemical composition of pods appear to have
been made in Rajasthan. *Acacia nilotica* pods have been found elsewhere in India to have CP values of 13.6 to 16.1% (of DM) (Lal 1977, Singh 1982). Khejri pods have been found to have CP values of 18.2% (of DM) in Haryana (Gupta et al. 1974a).

Chapter 9 discusses in more detail the feed value of WP foliage.

8.4. Feed budget of W Rajasthan.

The information available from various authors appears at first sight to indicate that it would be possible to formulate a feed budget for W Rajasthan, and the suggestions made by some of these authors have been that it is indeed possible to do so. However it has been impossible to obtain realistic figures on the average stocking density for various sites of even the 2 better studied fodder WP species (Khejri and Bordi). Therefore the only way to evaluate Ghosh's (1983) statement that enough animal fodder is produced in W Rajasthan if one takes into account the production of fodder WPs, is by estimating the levels of feed required given the livestock population in 1972 and to calculate the amount of feed which WPs would have to produce to meet the requirement. It should then be possible to evaluate if the WP stocking densities required to produce such quantities of forage are at all realistic.

However it must also be remembered that a considerable proportion of livestock migrate seasonally out of W Rajasthan each year in search of fodder (see section 7.1.4). No appropriate detailed information has been found concerning the numbers of various livestock types involved, their place of origin or the time spent on migration both within W Rajasthan or outside the area. Mann et al. (1977a) produced a table
of the "percentage of traditional livestock migration from different arid districts of Rajasthan". However it is of no use since it purely stated the proportion of livestock which migrated from each district for which they had figures in different years (no figures were provided for some districts in some years) as a percentage of the total livestock numbers which migrated (but only for those they had figures), without stating what the actual numbers were. Further some of these livestock are likely to have migrated between districts within W Rajasthan. No figures on the numbers of nomadic or semi-nomadic households have been found (eg. Bose et al. 1964, Malhotra 1977, 1978, 1984, and Malhotra et al. 1963). It is particularly amongst the owners of sizeable herds of small ruminants that migration takes place and Kalla et al. (1980) stated that "rearing of large flocks of sheep for wool and meat production is a major occupation of c. 400 000 families in the extreme arid region of W Rajasthan". It has not been possible to ascertain the reliability of this estimate (it appears to be high) but it seems to support Acharya's (1980) statement that a considerably proportion "80%") of livestock migrate each year from the arid districts to neighbouring districts in W and E Rajasthan and to other sites (see section 7.14). The important question as far as establishing a feed budget for W Rajasthan would be how many of these livestock migrate purely from the arid districts to the districts within W Rajasthan which have better feed resources during the dry season.

8.4.1. Feed demand

Feed requirements per unit weight of livestock vary according to a
whole range of factors which are animal specific (e.g. size of animal, 
sex, amount of work done, distance walked, growth rate, stage of 
pregnancy, milk yield). It is not surprising therefore that the 
literature on feed requirements of different types of livestock gives 
results which vary considerably even when converted to requirements per 
ACU \(W^{0.75}\). This is also partly because the term "feed requirement" 
is sometimes interchangeably used with "dry matter intake" which itself 
is highly variable according to season, fodder quality and the 
potential for selective feeding by the livestock (i.e. stocking 
density). There is a lack of accurate information on the feed 
requirements of various classes of tropical livestock for maintenance 
and production (Crowder et al. 1982, ILCA 1979). Too often, feeding 
standards for livestock in the tropics are still based on standards for 
temperate breeds in temperate regions (e.g. Kaul et al. 1982 for 
buffalo in India, Sen et al. 1978 for some of their feed ration for 
cattle in India). Yet it is increasingly becoming apparent that 
maintenance requirements of many tropical breeds are lower than for 
temperate breeds (e.g. Ikhatua et al. 1979, Mba et al. 1975). Their 
fodder intake levels may be considerably lower even when fed on the 
same diet (e.g. Mosi et al. 1976), and is generally considerably lower 
due to the lower average quality of natural feeds in the tropics (e.g. 
Crowder et al. 1982, McKay et al. 1969). The energy expenditure 
for grazing activities and walking are considerable. Wilson (1982a) 
calculated that the average yearly additional energy expenditure for 
such activities in pastoral cattle in Mali was 42% over the estimated 
minimum maintenance requirements. Ledger (1977 in Richardson 1983) in 
Kenya found that steers needed 24, 49 and 73% more of the same food to
maintain their body weight when they walked 5, 10 and 15 km per day as compared to animals kept inactive in pens. However most voluntary feed intake studies have been done in pens and those carried out under natural grazing conditions are subject to considerable error (Shaw et al. 1976).

Appendix 20 refers to a number of estimates of feed requirement and of fodder intake levels for cattle, sheep, goats, buffaloes and camels from various tropical countries and converted to "requirements" per ACU (W^{0.75}). The data are summarized in Table 8.6. For cattle the figures range from 3.5 kg (?DM) per ACU for a maintenance requirement for non producing animals in India (Sen et al. 1978) to 9.0 kg (?DM) for the higher values of fodder intake in East African zebu (Pratt et al. 1977) and Indian milk producing animals fed with good quality pasture (Ray 1978). For sheep and goats the values range from 3.0 to 7.5 kg (?DM) for a maintenance ration (Devendra et al. 1982) and an "average dry matter intake" respectively (Ghosh et al. 1980).

Mann et al. (1975) estimated that an ACU in the NW arid zone of India "requires" 2.5 tonnes (?DM) of forage annually (ie. 6.9 kg daily). More recent authors from CAZRI and elsewhere in Rajasthan have relied on this estimate for their calculations. However as stated in Appendix 20, there are doubts concerning what this estimate refers to in terms of a "feed requirement" and concerning how it was derived. Further, the estimates given by CAZRI (1983) and Ghosh et al. (1980) (see Appendix 20.15 and 20.16) for the "average intake levels" of sheep and goats seem to be high compared to those from other sources.

For the purposes of this analysis it is assumed that the daily
Table 8.6. Estimates and measurements of feed requirements of various livestock types in the tropics (Kg ?DM/ACU, W0.75) (based on Appendix 20).

<table>
<thead>
<tr>
<th>Cattle</th>
<th>Sheep/Goats</th>
<th>Camel</th>
<th>Buffalo</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1/M</td>
<td>2/I</td>
<td>3/P</td>
</tr>
<tr>
<td></td>
<td>estimates</td>
<td>estimates</td>
<td>measurements</td>
</tr>
<tr>
<td>Notes: 1/ M = estimates and measurements of &quot;maintenance&quot; feed requirements. 2/ I = estimates and measurements of voluntary dry matter intake levels. 3/ P = estimates and measurements of feed requirements to achieve some production. 4/ The numbers in brackets following estimate and measurement figures refer to the appropriate entry in Appendix 20.</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>7.2 (0)</th>
<th>7.3 (5)</th>
<th>3.0(11)</th>
<th>5.2(17)</th>
<th>5.5(11)</th>
</tr>
</thead>
<tbody>
<tr>
<td>M</td>
<td>3.5-5.9(6)</td>
<td>6.0-7.5(6)</td>
<td>4.2-7.1(6)</td>
<td>4.8(17)</td>
<td></td>
</tr>
<tr>
<td>I</td>
<td>4.3-5.3(6)</td>
<td>5.1-6.4(6)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>P</td>
<td>6.0 (7)</td>
<td>7.5-9.0(7)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(mean)</td>
<td>(5.7)</td>
<td>(6.8)</td>
<td>(6.8)</td>
<td>(3.9)</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>7.4 (3)</th>
<th>4.6(13)</th>
<th>5.8(10)</th>
<th>5.5(9)</th>
<th>5.0-7.0(12)</th>
</tr>
</thead>
<tbody>
<tr>
<td>M</td>
<td>6.9-7.5(3)</td>
<td>4.3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>I</td>
<td>4.5-5.7(3)</td>
<td>5.0-6.2(15)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>P</td>
<td>4.5-6.3(3)</td>
<td>5.0-7.5(16)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(mean)</td>
<td>7.3 (4)</td>
<td>4.5-9.0(5)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(6.5)</td>
<td>(5.2)</td>
<td>(5.7)</td>
<td>(6.0)</td>
<td></td>
</tr>
</tbody>
</table>
maintenance requirements of an inactive ACU in W Rajasthan is 5.1 kg (?DM) of fodder. This estimate is derived from the means of the maintenance rations from Table 8.6, assuming that cattle (including buffaloes) and small ruminants (plus camels) comprised 2/3 and 1/3 respectively of the ACUs in W Rajasthan in 1972 (see Appendix 7A).

Since a considerable proportion of livestock (particularly sheep, goats and camels) cover long distances in search of grazing, it is estimated that the average maintenance requirements for a "normally active" ACU in W Rajasthan is 20% greater than for inactive livestock (see Appendix 20) - ie. 6.1 kg (?DM) daily. If these assumptions are realistic it follows that an average ACU only starts producing (weight gain, reproduction, milk production) if more than 6.1 kg (?DM) of fodder is ingested daily. This figure coincides with the mean of the measured intake levels given in Table 8.6, assuming the same proportions of livestock types as for the calculation of the "inactive maintenance requirement" above.

Considering that the quality of a considerable proportion of the fodder is generally low in W Rajasthan (see Section 8.1.3, 8.2 and Chapter 9) it would be surprising if the daily feed intake levels averaged over the year were higher than 6.1 kg (?DM) per ACU. Nevertheless, assuming that the requirements for the average production levels found in an average rainfall year are 5% greater than inactive maintenance levels, the average feed intake of a productive ACU would be 6.4 kg (?DM) assuming that the feed quality is not limiting intake. These estimates broadly agree with further data provided by Crowder et al. (1982), McCammon et al. (1981) McKay et al. 1969 and Mosi et al. (1976).
A ration which contains 5% more feed than for the normal activity maintenance diet is thought to be generous for the production level found in livestock in W Rajasthan. Cows calve on average once in two years (Crotty 1980) and daily milk yields are not likely to be greater than one litre (see Appendix 20, 6) (Brumby 1981), and 150 litres/year (Bentley 1984). Yet such a ration is smaller than that estimated by Mann et al (1975) and other authors since then for an ACU in W Rajasthan (see above) (ie. 6.9 kg daily).

Hence the annual fodder requirements for an ACU on an inactive maintenance diet, a normal activity maintenance diet and production diet would be 1.86, 2.23 and 2.34 tonnes (?DM) respectively. Although an inactive maintenance diet may be seen as being academic and not an option for livestock as a whole in W Rajasthan, it may be relevant in situations where livestock are stall fed and during years when fodder is particularly scarce. For the total livestock population of 6.285 M ACUs for W Rajasthan in 1972, the equivalent amounts would have been 11.69, 14.02 and 14.71 M tonnes (?DM), if all the livestock had remained throughout the year in the State. It must be emphasized that for the population of livestock of W Rajasthan as a whole the figure of 11.69 M tonnes (?DM) for an "inactive maintenance diet" is academic since most livestock do walk and that quality of fodder would therefore amount to a sub-maintenance diet.

8.4.2. Fodder supply.

Table 8.7 summarizes the quantities of fodder estimated to be available from pastures and agricultural residues during a normal rainfall year and a moderate drought year. Table 8.8 gives the
Table 8.7. Fodder supply from pastures and agricultural residues in W Rajasthan according to various scenarios. (M tonnes ?DM/year).

<table>
<thead>
<tr>
<th>Pasture</th>
<th>Crop residue</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average rainfall</td>
<td></td>
<td></td>
</tr>
<tr>
<td>year</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A1</td>
<td>2.152</td>
<td>4.698</td>
</tr>
<tr>
<td>A2</td>
<td>2.754</td>
<td></td>
</tr>
<tr>
<td>Moderate drought</td>
<td></td>
<td></td>
</tr>
<tr>
<td>year</td>
<td></td>
<td></td>
</tr>
<tr>
<td>B1</td>
<td>1.635</td>
<td>2.930</td>
</tr>
<tr>
<td>B2</td>
<td>2.065</td>
<td></td>
</tr>
</tbody>
</table>

Notes: A1/B1 assuming 70% pasture utilization (see section 8.1.2) A2/B2 assuming 89% pasture utilization.
Table 8.8. Annual fodder required from WPs to meet the deficit if livestock are to get all their feed requirements from W Rajasthan.

<table>
<thead>
<tr>
<th>Type of feed requirement</th>
<th>Total fodder requirement (M tonnes ?DM)</th>
<th>Pasture and residue production (M tonnes ?DM)</th>
<th>Total WP production required (M tonnes ?DM)</th>
<th>Average WP production (tonnes ?DM/ha) from cropland</th>
<th>Average WP production (tonnes ?DM/ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inactive</td>
<td>11.69</td>
<td>6.850 (A1)</td>
<td>4.84</td>
<td>0.271</td>
<td>0.464</td>
</tr>
<tr>
<td></td>
<td></td>
<td>7.452 (A2)</td>
<td>4.24</td>
<td>0.237</td>
<td>0.406</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4.565 (B1)</td>
<td>7.13</td>
<td>0.399</td>
<td>0.683</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4.995 (B2)</td>
<td>6.70</td>
<td>0.375</td>
<td>0.642</td>
</tr>
<tr>
<td>Maintenance for Normal Activity</td>
<td>14.02</td>
<td>6.850 (A1)</td>
<td>7.17</td>
<td>0.402</td>
<td>0.687</td>
</tr>
<tr>
<td></td>
<td></td>
<td>7.452 (A2)</td>
<td>6.57</td>
<td>0.368</td>
<td>0.629</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4.565 (B1)</td>
<td>9.46</td>
<td>0.530</td>
<td>0.906</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4.995 (B2)</td>
<td>9.03</td>
<td>0.506</td>
<td>0.865</td>
</tr>
<tr>
<td>&quot;Normal&quot; Production</td>
<td>14.71</td>
<td>6.850 (A1)</td>
<td>7.86</td>
<td>0.440</td>
<td>0.753</td>
</tr>
<tr>
<td></td>
<td></td>
<td>7.452 (A2)</td>
<td>7.26</td>
<td>0.407</td>
<td>0.696</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4.565 (B1)</td>
<td>10.15</td>
<td>0.569</td>
<td>0.972</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4.995 (B2)</td>
<td>9.72</td>
<td>0.544</td>
<td>0.931</td>
</tr>
</tbody>
</table>

Notes:
1/ Based on assumptions given in section 8.4.
2/ Based on Table 8.5.
3/ A1 = Average rainfall year and 70% pasture utilization. A2 = Average rainfall year and 89% pasture utilization. B1 = Moderate drought year and 70% pasture utilization. B2 = Moderate drought year and 89% pasture utilization.
4/ Yields of WP fodder/ha on the basis of 17.853 M ha on which fodder WPs can reasonably be expected to exist (includes "forest", "other uncultivated land", "fallow land" and "net area sown" (see Appendix 6).
5/ Yields of fodder/ha which would be required from WPs if these occurred only on "cultivated" and "current fallow lands" - i.e. 10.438 M ha (see Appendix 6).
estimated quantity of fodder which WPs should produce to satisfy the requirements in years of average rainfall and of moderate drought, and for the 3 levels of estimated fodder requirement ('inactive maintenance', 'normal activity maintenance' and 'production diet').

Table 8.8 also gives the average fodder yield/ha which WPs would have to produce to meet this requirement assuming that they occur either on all grazing and cultivated land or only on land which has, in the recent past, had some degree of protection from grazing i.e. "cultivated" and "current fallow" land (i.e. land on which tree densities are likely to be higher if encouraged by the farmers).

Table 8.8 shows that if fodder WPs are to supplement the fodder available from pastures and crop residues and meet the fodder requirements of livestock as Ghosh (1983) has suggested, they would have to produce 4.24 to 10.15 M tonnes (DM) or 36 to 69% of the fodder supply respectively depending on whether this was to fulfil the requirements for inactive maintenance (in effect sub-maintenance) in a normal year with full utilization of pasture resources or for "normal production" in a moderate drought year assuming a "proper pasture utilization factor" (70%, section 8.1.1.). If the higher estimates which have been given by various authors for Khejri, Bordi and other fodder WPs are in fact correct, the year-round fodder requirement for the higher level of requirement assumed above (i.e. 10.15 M tonnes DM) could easily be satisfied. Assuming conservatively that half of the cultivated lands of W Rajasthan occur in areas receiving more than 300 mm of rainfall, this requirement could be met by a density of only 40 productive Khejri trees/ha on cropland alone, without a need for any other WP species (see Table 8.8 and section 8.3.1, iii) [5.219 M ha x
40 trees x 20 kg) + (5.219 M ha x 40 trees x 30 kg) = 10.438 M tonnes DM). It would only require 2 to 3 *Ailanthus excelsa* trees/ha of cropland to meet the same requirement, if the estimate given by Bhandari *et al.* (1972) and repeated since by others (eg. Singh 1982) is correct.

However since each year an unknown but apparently considerable proportion of livestock migrates to neighbouring states in search of food, and since livestock mortalities are also known to be high in dry years, the suspicion that the lower estimated yields which were given in section 8.3.1, iii are correct is reinforced. The fact that the Livestock Division of CAZRI believes that there is enough fodder in W Rajasthan if the production of fodder WPs is taken into account (Ghosh 1983) appears to depend entirely on its acceptance of the high yield estimates for Khejri (Appendix 13.3) and Bordi (Appendix 14.5) (Bohra *et al.* 1980, 1981). If Ghosh calculated the quantity of fodder which WPs need to provide to make up the shortfall on the basis of Ahuja's (1977) estimates of the 1975 requirements and of the supply from rangelands and crop residues, the fodder WPs would have to have provided 6.664 M tonnes (?DM) or 40% of their estimated requirement; this would require even fewer fodder WPs/ha.

If the estimates of the more realistic lower yields are accepted, the average production/ha of fodder WPs would have to be equivalent to an average of 115 Khejri trees and 300 Bordi bushes/ha over all the cultivated lands and lands available for grazing in order to satisfy the fodder shortfall for livestock which have a "normal" level of production during a normal rainfall year and assuming a maximum pasture utilization factor (89%) (for assumptions and calculation see Appendix
21). Such an average density is thought to be unrealistic, given the evidence in section 8.3.2. This explains the need for livestock to migrate out of the area given the assumptions stated.

It is acknowledged that the total amount of fodder available in W Rajasthan is highly sensitive to variations in the levels of production of agricultural residues. Considering the estimates given in section 8.2 (and the even larger estimate made by Ahuja 1975) that agricultural residues contribute such an important proportion of the average fodder budget, it is surprising that assessments of their production levels do not appear to have been made in W Rajasthan.

It is clear from Table 8.7 that, for W Rajasthan as a whole, the estimated contribution of fodder from pasture is considerably smaller than that from crop residues. The estimated yield/ha of available fodder from irrigated croplands is over 12 times greater than that from grazing lands. Table 8.9 (derived from Appendix 9) shows that the estimated quantity of available feed/ha of cultivated rainfed land is as important as that from pastures and in a normal rainfall year may even be greater than for pasture.

During the monsoon (c. 3 months) livestock do not have access to cultivated fields, although no doubt some fodder is provided in the form of weeds to some stall fed animals. During this period the estimated fodder requirement from grazing land would be more than 3.68 M tonnes (DM). A 5% allowance for production over an active maintenance diet is conservative during the growing season since livestock eat more during this period and store body reserves for the dry season. Yet the estimate for total fodder production from the ground storey component of the grazing lands (Table 8.7) shows that
Table 8.9. Average estimated yield of fodder from grazing lands and from agricultural residues on rainfed land (tonnes ?DM/ha p.a.)
(derived from section 8.1.1, 8.2.2 and Appendix 9).

<table>
<thead>
<tr>
<th></th>
<th>Grazing land (tonnes ?DM/ha p.a.)</th>
<th>Rainfed cultivated land (tonnes ?DM/ha p.a.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal rainfall yer</td>
<td>A1 0.25</td>
<td>0.37</td>
</tr>
<tr>
<td></td>
<td>A2 0.32</td>
<td></td>
</tr>
<tr>
<td>Moderate drought ye</td>
<td>B1 0.19</td>
<td>0.17</td>
</tr>
<tr>
<td></td>
<td>B2 0.24</td>
<td></td>
</tr>
</tbody>
</table>

Notes: 1/ see notes in Table 8.6.
2/ the figures refer to average fodder yield/ha of total area under rainfed cultivation.
such a quantity of fodder is not available. Even if livestock were on an "inactive maintenance" diet (5.1 kg/ACU/day) with a further 5% allowance to allow for growth in a cut and carry system, the average requirement during the 3 monsoon months would be 3.069 M tonnes i.e. about 10% higher than the estimate of maximum average pasture available during an average rainfall year (see Table 8.7). The reasons for such an estimated shortfall could be due to an over-estimate of feed requirements per ACU. This is certainly possible given that the assumption used here concerning feed requirements for the maintenance diet of an ACU was derived from the mean of a number of maintenance rations given in Table 8.6. However if a lower value is more realistic, the discrepancy between the actual requirements and those quoted by animal and range scientists in W Rajasthan is even greater than with the values adhered to here.

The possibility of an under-estimate for the average yield of pastures cannot be discounted (see discussion in section 8.1). Further some fodder for a proportion of the livestock during the monsoon may originate from cultivated land in the form of weeds and herbage cut from field edges. It could also be that some livestock obtain a proportion of their diet from browse even during the wet season. In the dry zone of N Kenya, Lusigi (1981) and Said et al. (1983) have shown that camels and goats (and to a certain extent sheep) eat a considerable amount of browse during the wet season and Lusigi stated that "smallstock surprisingly appeared to eat more browse in the wet seasons rather than in the dry seasons". However, no feeding behaviour studies appear to have been carried out in W Rajasthan under natural grazing conditions so it is not possible to ascertain the likely extent
of the reliance of different types of livestock on browse during the wet season. However such studies would seem to be crucial to an understanding of the amount of WP foliage which would be available as "carry over fodder" for harvest during the early part of the dry season and of the extent to which fodder WPs may regenerate and grow to mature trees under different livestock densities.

8.5. Conclusions.

There is a considerable amount of published information resulting from more than 20 years of research in W Rajasthan on range management, livestock nutrition and production, fodder production of WPs and their population densities. It was therefore thought that it should be possible to understand why there have been considerable discrepancies between authors concerning both the feed supply and demand situation in the area and the role of fodder WPs in meeting the fodder shortages (see Chapter 7). It was also thought that such an understanding would enable one to identify which hypotheses are most likely to be correct, if necessary to derive a more realistic fodder budget and to quantify the impact which fodder WPs have or could have on the fodder supply (and therefore on livestock production).

The survey of the literature covering the topics under consideration and which are specifically related to W Rajasthan included more than 100 journal publications and papers, 6 CAZRI annual reports, 10 CAZRI technical bulletins and monographs, proceedings of 2 international symposia, proceedings of one national symposium specifically on agroforestry and 2 books (one of them being ICAR's contribution to the UN Conference on Desertification and its' Control
The pasture research has concentrated mainly on developing technologies for pasture reseeding with perennial grasses and legumes, and on the optimum management regimes for such perennial pastures (eg. type of grazing rotation, stocking density). The livestock production research has concentrated on determining optimum stocking densities for maximum productivity, on the effects of water restriction on various aspects of livestock physiology and productivity, and on some aspects of the nutrition of livestock fed solely on WP fodder (see Chapter 9). Some information is available on the chemical composition of fodder WPs.

Information does not appear to be available on the actual yields of pastures in grazing lands (composed mainly of annuals) with realistic stocking densities (see section 8.1). No detailed surveys appear to have been carried out to assess the ways in which the farming populations manage their different types of livestock (including different feeding strategies) or even the levels of production which different types of livestock sustain in years of varying rainfall. There does not appear to be any information on the fodder requirements to sustain various levels of livestock production (see section 8.4.1). The information concerning migrating livestock is not detailed enough to allow estimates to be made of the feed requirements met by areas outside W Rajasthan. No detailed information appears to be available on yields of crop residues under local conditions and on how these fluctuate with varying rainfall or on the contribution of weeds or herbage from field edges to the fodder supply particularly during the monsoon.
The information which is available concerning the foliage yields of fodder WPs is very contradictory. One explanation for at least some of the differences between yields quoted (even from the same institute - CAZRI) may lie in the fact that the harvest from trees which have never been lopped are likely to be considerably higher than that from trees which have been previously lopped, even if the trees are of the same dbh size. Foliage yields are often given in relation to a subjective assessment of the size of a tree (eg. "average mature tree") with no reference to the physical dimensions. As has been discussed in section 8.3.1, it seems that a mature tree on poor sites in the area may be at most 4 m tall while on the best sites may reach 15 m.

Methodological weaknesses in some of the research and possible mistakes in the interpretation of data have already been mentioned (section 8.3.1). The ecological and vegetation surveys which have been undertaken may have met their objective of determining what the climax vegetation is likely to be on various sites, along with the maximum size of various tree species and possible total above ground biomass. However they have not led to relevant or realistic information being published concerning the average fodder WP stocking densities for different sites and land use categories.

Consequently the majority of the available information is not appropriate for determining functional relationships concerning various components of the farming systems of W Rajasthan or for predicting likely developments, even though some authors have used the information in such a way. It seems apparent that the reason why authors (originating even from the same institute) have presented conflicting results concerning the fodder situation in W Rajasthan is that there is
little understanding - or at least critical appraisal - of the relevance and limitations of information provided by other disciplines, and of the way it has been obtained. Publications often do not describe the methodology which has been followed to obtain the results which are given, in enough detail to enable an evaluation to be made of the reliability or relevance of the information. If information on a specific component of the farming system is not available from W Rajasthan, the appropriate information appears to be sought from other sources and may be uncritically applied to the area under consideration (eg. crop residue yields, livestock feed requirements). The bases underlying many assumptions which are made are often not given.

Even though it has not been possible on present evidence to evaluate the contribution of fodder WPs to the fodder and fuel supply of W Rajasthan, a number of possible hypotheses can be drawn concerning the development of farming systems in the area and the role which fodder WPs may have. However to lend more support to these hypotheses a closer look at the feed value of WP fodder to different types of livestock and at the contribution which fodder WPs can make on cultivated land is desirable. These topics are discussed in Chapter 9.
CHAPTER 9

The Role of Agro-Silvopastoralism in W. Rajasthan

The previous chapter has shown that on currently available evidence it is not possible to quantify the contribution which fodder WPs make to W Rajasthan's fodder budget. Since the fodder supply does not seem to meet the demand even in good years (see section 8.4.2), the contribution of fodder from WPs is likely to be important to livestock nutrition, particularly if the quality of their foliage is as high as suggested by CP values. However, in the international literature, opinions concerning the nutritional value of fodder WPs and of their role in livestock production are highly contradictory. In a world-wide review of the value of WP fodder, Wilson (1969) suggested that even though CP values of foliage may be high it had not yet been shown that WP fodder has an important contribution to make to the the nutrition of livestock. Wilson et al. (1980) stated that in view of the low nutritive value of WP fodder in the semi-arid and arid areas of Australia, it is important only during periods of nutritional stress and then only for survival purposes. Gintzburger (1984) suggested that the prospects for the success of fodder WPs in the semi-arid and arid areas of the Middle East and North Africa are slim, particularly because of major management problems. On the other hand there is increasing evidence that the fodder of some WP species may have a considerable beneficial impact on livestock productivity, particularly during the critical dry periods of the year and even during drought years (eg. Gray 1970, Openshaw 1979, Von Maydell 1978 for general
comments; for *Leucaena leucocephala* foliage eg. Foster *et al.* 1983, Partridge *et al.* 1974; for *Giricidia sepium* foliage eg. Chadokar *et al.* 1980, Chadokar, 1983; for *Prosopis juliflora* pods eg. Kargaard *et al.* 1976; for *Acacia tortilis* pods eg. Cisse 1983). Further, fodder WPs have been valued and promoted for millenia by farming communities in various climatic zones and regions where fodder has been seasonally in short supply (for further discussion on some of the factors to take into account in an evaluation of the nutritive value of WP fodder see Annexe II). Section 9.1 therefore looks in more detail at the nutritive value of the better fodder WPs of W Rajasthan.

Section 9.2 concentrates on the potential contribution which fodder WPs occuring on private cropland in rainfed areas can make to livestock nutrition and production.

Rainfed areas were chosen because they represent the greatest proportion of cultivated lands and some districts have very little irrigation (see Table 9.1). The evidence given so far also suggests that irrigated areas have better and more reliable fodder supplies. Districts such as Jodhpur, Churu and Nagaur have a small proportion of land available for grazing hence the fodder WPs are likely to be particularly important in such areas. The reason for choosing privately owned cropland is that this is where the farmer has a considerable degree of control over the management of the resources at his disposal. As livestock densities are so high on grazing lands, it is hard to see how fodder WPs can get established in such areas. However much research has shown the extent to which range production can be improved with better management practices under research station conditions (eg. Paroda *et al.* 1980), Jodha (1977) has revealed that
not a single panchayat (smallest civil administrative unit) in W Rajasthan had taken any steps to manage or develop village pastures and forests, uncontrolled and unrestricted grazing being the rule.

Table 9.1. Area of privately owned land, cultivated land and irrigated land in the districts of W Rajasthan (derived from Jodha 1977).

<table>
<thead>
<tr>
<th>District</th>
<th>% area allocated to private cultivation</th>
<th>Net cultivated area as % of area allocated to private cultivation</th>
<th>Net irrigated area as a % of net cultivated area</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jaisalmer</td>
<td>13.3</td>
<td>42.9</td>
<td>0.16</td>
</tr>
<tr>
<td>Bikaner</td>
<td>38.7</td>
<td>57.7</td>
<td>0.03</td>
</tr>
<tr>
<td>Barmer</td>
<td>74.3</td>
<td>67.2</td>
<td>0.92</td>
</tr>
<tr>
<td>Jodhpur</td>
<td>77.8</td>
<td>80.6</td>
<td>1.96</td>
</tr>
<tr>
<td>Churu</td>
<td>88.9</td>
<td>87.6</td>
<td>0.02</td>
</tr>
<tr>
<td>Nagaur</td>
<td>85.5</td>
<td>96.6</td>
<td>1.80</td>
</tr>
<tr>
<td>Jalore</td>
<td>80.6</td>
<td>93.3</td>
<td>7.10</td>
</tr>
<tr>
<td>Pali</td>
<td>65.5</td>
<td>86.7</td>
<td>17.22</td>
</tr>
<tr>
<td>Sikar</td>
<td>80.3</td>
<td>97.1</td>
<td>5.53</td>
</tr>
<tr>
<td>Sirohi</td>
<td>42.8</td>
<td>86.5</td>
<td>23.34</td>
</tr>
</tbody>
</table>

Paroda et al. (1980) admitted that fencing is essential before any management programme is launched in the arid regions of W Rajasthan. However the costs of upgrading rangeland are high given the present low productivity of livestock. Ahuja (1977) stated that in 1975 the costs of such improvements ranged from Rs 500 to 1400 (about £28 to £78) per ha (including fencing) on the basis of 1000 ha blocks
and depending on land form, locality etc. Hence it is suggested that the options for improving fodder production and quality which have the most chances of success are on land which is privately owned. It must be admitted that the considerable amount of research which has been done at CAZRI on fodder WP pasture mixes is seen as being largely irrelevant given the circumstances of W Rajasthan, even though it has been shown that considerable gains can be obtained by a physically integrated production of trees and pasture (eg. Shankar 1981).

Section 9.3 shows the contribution which some fodder WP species occurring on private land can make to the farm's fuel requirements.

Section 9.4 discusses in detail the role which fodder WPs may actually and potentially have in W Rajasthan in the context of observed trends in various components of the farming systems.

9.1. Nutritional value of fodder WPs.

An evaluation of the actual contribution of fodder WPs to livestock production necessitates not only an assessment of the quantities available, relative to other sources, but of their nutritional value. Ultimately, the assessment of the nutritional value must be in terms of livestock response to the actual levels of intake of the various sources of fodder available.

Some indications of the nutritive value of WP fodder can be obtained from livestock owners who have considerable relevant knowledge gained by trial and error over centuries. Their knowledge includes the value of different fodder WP species to different types of stock, the optimum harvesting season and the optimum proportion of fodder from different types of forage (eg. see Annexe II).
The assessment of nutritive value by research requires that the response of livestock be measured to diets which are either representative of those which actually occur under farm conditions or can realistically exist. This may be in terms of the proportion of different fodders, the season of their harvest or whether the foliage is fresh or dry.

9.1.1. Traditional feeding strategy and perception of nutritional value.

1) Ailanthus excelsa and Albizia lebbek.

There appears to be no detailed information concerning the traditional feeding practices of Ailanthus excelsa and Albizia lebbek in W Rajasthan. This is likely to be because although these species have been successfully planted in the area (Mann et al. 1984, Singh 1982), the literature indicates that they occur, traditionally, only in small numbers on better sites (eg. Saxena 1977). In the plains and hills of Jammu State the leaves of Albizia lebbek have been traditionally fed to cattle and buffalo during the dry winter months. The foliage is sold to migrating herdsman who claim that the foliage has an excellent effect on the health and milk yields of their stock (Khajuria 1965). In the wetter part of E Rajasthan Ailanthus excelsa foliage is sold for about Rs 40 per 40 kg (ADM) (Hughes 1984).

ii) Prosopis cineraria.

It has already been mentioned (section 8.3.1) that Khejri is traditionally lopped or its foliage stripped in the months of October to January. Settled agriculturalists store this fodder for the dry season. It is also sold in towns, particularly for goats kept by
butchers, at Rs 30 to 35 (about £1.60 to £2 at late 1970's prices) per 40 kg (ADM) (Purohit et al. 1980). Regrowth of small green twigs and leaves is also harvested and sometimes sold (Mann et al. 1983, Purohit et al. 1980, Saxena 1980). The semi-nomads lop Khejri throughout the dry season on their migratory routes to feed cattle, goats, sheep and camel. It is not clear from the literature if Khejri, as dry season fodder for sheep and goats held on farms, is harvested as required or if the animals are fed dried leaves. Bohra (1983) and Purohit et al. (1980) have suggested that dry Khejri leaves are fed to cattle. Usually, they are first boiled and then mixed with agricultural residues. Patel et al. (1978) found between 1958 and 1960 that Khejri was extensively used as a green fodder supplement for cattle during the dry season. However, Saxena (1980) claimed that dry winter-lopped Khejri fodder is used extensively for feeding milk producing livestock. When camels are used for work they are either totally stall-fed, partly on WP fodder, or partially stall-fed and allowed to browse for part of the day (Patel et al. 1978).

In reality very little has been recorded concerning the traditional feeding strategy of different livestock species and what their responses are to Khejri fodder supplementation. Some of the suggestions do not seem to agree. The need for boiling dry Khejri leaves for cattle suggests that its digestibility or palatability is low for cattle when unprocessed (see Annex II for similar WP fodder treatment in other areas). The indications are that camel and goats can obtain a greater proportion of their diet from Khejri. There is a popular saying in W Rajasthan that "death will not visit a man even at the time of famine if he has a Khejri tree, a goat and a camel"
iv) Zizyphus nummularia.

Bordi fodder is traditionally harvested in the winter. In drought years however the bushes are also cut during April/May (Purohit et al. 1981) and they are heavily browsed during the summer months. Purohit et al. (1981) stated that cattle browse the shrub when the shoots are tender but when they become woody and thorny only goats and sheep (and presumably camel) can browse it.

The dry fodder fetches Rs 20 to 35 (£1.1 to £2) per 40 kg (ADM) according to season and availability. Purohit et al. (1981) stated that it is a highly valued fodder for goats, camels, sheep and cattle and can be given either exclusively as the diet or with Khejri forage or crop residues. They implied that the intake of wheat and millet residues which are not particularly palatable is improved by mixing with 50% of Bordi fodder. Milk production is also supposed to be promoted. Saxena (1981) stated that cattle are given dry Bordi fodder during the lean months while Patel et al. (1978) suggested that it is given as a green fodder supplement.

As for Khejri fodder there seems to be little detailed information concerning traditional feeding of Bordi fodder to livestock. The reports do suggest however, that milk production is promoted and that the four main types of livestock can be given it as an exclusive diet. Further, it is implied that the intake of nutrient-poor crop residues is improved by including a proportion of Bordi foliage in the diet.
9.1.2. Research results and nutritive value.

The rationale that the better fodder WP should be of considerable importance to livestock nutrition relies primarily on their usually high CP values and, hence, statements such as "they are especially important for sustained animal production in these regions (W Rajasthan)" (eg. Bohra et al. 1981) are frequent. It is generally argued that if the CP levels in herbage intake fall below 7% in tropical forages, the microbial activity in the rumen is depressed by lack of nitrogen which results in a slow rate of passage of the digesta and therefore in considerably reduced voluntary intake. Further when CP levels fall below 6% there is a marked decline in total carbohydrate digestibility (Crowder et al. 1982, Minson 1982a, Whiteman 1980). Norton (1982) suggested however that a CP value of 9% (DM) is considered the minimum level for ruminant requirements while 15% is required for lactation and growth.

The important points are therefore that voluntary intake should not be limited by low fodder quality and that the fodder should be digestible enough in terms of DM and CP to obtain the necessary energy and protein requirements.

Hence, theoretically, supplementing agricultural residues and pasture which have low CP values with WP fodder should increase the utilization efficiency of the low quality fodder (see Torres' and Minson's relationships in Figs. 9.1 - 9.3), improve livestock nutrition and increase secondary productivity. This has been found to be the
Torres' (1984) relationship is that accepted for herbaceous forages; lettered points refer to feeding trials in India with different fodder WPs and livestock types (letters refer to references in Appendix 24. A, B).

Fig. 9.1. Relationship between crude protein digestibility and crude protein content of fodder.
Torres' (1984) relationship is "that accepted for herbaceous forages"; Minson's (1982) relationship is that "which applies to a very wide range of protein levels in both temperate and tropical feeds (incl. legumes and grasses, different types of livestock and levels of fertilizer applied); lettered points as for Fig. 9.1).
Minson's (1982) relationship refers to temperate grasses and legumes; the derived relationship assumes a 15\% lower dry matter digestibility for herbage in Rajasthan, see Appendix 24C for explanation; lettered points as for Fig. 9.1.

![Graph showing the relationship between dry matter digestibility and crude protein of fodder](image)

**Fig. 9.3** Relationship between dry matter digestibility and crude protein content of fodder.
case when low quality roughage is supplemented with concentrates (eg. Andrews et al. 1972) but not always (eg., Horton et al. 1976). Jones (1979) reported on a study with steers, where 12.3 kg of sorghum hay was needed for each kg of liveweight gain, while only 7.6 kg of a diet containing sorghum hay and 20% leucaena foliage was required for each kg gain. Moran et al. (1983) found with Zebu cattle and Swamp buffalo fed on a rice straw diet, that the rate of passage of digesta was increased, balances of dietary nutrients and levels of rumen metabolites improved with a supplement of Leucaena leucocephala.

The results of the feeding trials which have been undertaken with various livestock types on exclusive diets of Ailanthus excelsa, Albizia lebbek, Khejri and Bordi are given in Appendix 24A. Further information concerning these trials is given in Appendix 24B and the results concerning their CPD, DCP and DMD are summarized in Figs. 9.1, 9.2 and 9.3; these indicate that CP levels cannot reliably be used to predict fodder quality in fodder WPs.

As stated in Appendix 24B there are a number of problems facing an attempt to extrapolate the results of these feeding trials to an evaluation of the role of WP fodder to livestock nutrition and production under farm and range conditions.

The season of foliage harvest has seldom been mentioned, yet there may be seasonal differences in the feed value both in terms of variations in the levels of the useful chemical constituents (see Section 8.3.3 and Appendix 23) and in the levels of components which are detrimental to the nutritional value. For Khejri foliage, Bhandari et al. (1979) measured tannic acid levels of 2.5% (DM) while Bohra (1980) and Gupta (1967 in Bohra et al. 1980) measured levels of 11.6%
for monsoon-harvested and 15% (DM) for winter-harvested Khejri fodder respectively. Tannins are known to inhibit protein digestibility (McLeod 1974). Malik et al. (1970) stated that their trials showed that the DM intake of summer lopped Bordi by sheep was lower than that which is winter lopped.

There are indications that livestock which have had longer experience of a diet of WP fodder may improve the utilization efficiency of that fodder. In two trials (Appendix 24A,B; D/L) the results suggest that DM intake and utilization efficiency of Albizia lebbeck and Bordi were improving towards the end of the trial period. In Nigeria, Carew (1980) found that goats and sheep, fed on an exclusive ad lib. diet of Gliricidia sepium, showed a sharp drop in weight at the beginning of the experiment. Mean daily DM intake (as a percentage of body weight) dropped from c. 5.5 in the first week for goat to c. 4.5 in the 5th week and increased thereafter to c. 8.6 in the 21st week. For sheep, the respective values were 5.4 in the first week, 4.0 in the 7th week and 8.3 in the 21st week. The initial weight was regained by the 9th week in goats and by the 15th week in sheep. However, the length of most of the trials quoted in Appendix 24A were shorter than the time required for goats to start increasing their intake in Carew's (1980) trial and all were shorter than the time taken by sheep to increase intake. The question therefore arises as to whether livestock under farm and range conditions may utilize the fodder WPs more efficiently than shown for many of the points in Figs. 9.1, 9.2 and 9.3 because they are more used to WP fodder. Only one of the trials (Appendix 24B; D) mentioned the feeding management of the
livestock prior to the trial period and that was one where the stock had no previous exposure to the WP fodder; their intake increased over the trial period.

All the trials with Khejri and Bordi where the status of the leaves was given (i.e. green or dry) were concerned with dry fodder. Singh et al. (1977) (Appendix 24B; B) showed that the DCP intake from green leaves of *Ailanthus excelsa* was almost double that of dry leaves even though the latter were supplemented with molasses. Hence the feeding value of browse or fresh foliage could be considerably different to that of dried harvested fodder.

All the trials which are referred to in Appendix 24A investigated the nutritive value of WPs as exclusive diets (except for the addition of salt in some trials). However it is unlikely that under farm or range conditions livestock feed exclusively on only one WP species. In particular camel and goats may obtain most of their diet from browse or lopped WP fodder, but it is likely to be composed of a mixture of species. Such a mixture may influence the utilization efficiency of the diet; for instance, it has been suggested (Bohra et al. 1981) that a high lignin content limits the digestibility of Bordi fodder while a high tannin content is thought to limit the digestibility of Khejri.

Further, many livestock must feed on a mixture of WP fodder and pasture and/or agricultural residues. The only trial which investigated the value of WP fodder as a supplement to agricultural residues (wheat straw) showed that the rams lost weight when fed *Ailanthus excelsa* with straw (Bhandari et al. 1973) compared to
weight gains when fed exclusively on A. excelsa (Bhandari et al. 1972, Appendix 24A,B). However the animals were fed solely on A. excelsa leaves in the morning and exclusively on straw in the afternoon which may not be particularly representative of how livestock normally obtain their diets. Further the livestock concerned might have lost even more weight on a diet of wheat straw alone. It is possible that it is the inclusion of the low value wheat straw which reduced the CP digestibility of the diet and reduced the overall intake level by 37% compared to an exclusive diet of A. excelsa.

It is likely that feeding trials in pens, where animals have a limited choice of foliage, only indicate the likely response which can be expected with animals which are stall-fed on the same type and quality of fodder. Animals on the open range are known to be able to select plant parts which are considerably different in quality from the average for the vegetation or even for a particular plant's foliage. Results from one set of observations with fistulated cattle have shown that the diet contained 66% more CP than hand collected samples (Bredon et al. 1967 in Wilson 1969). Mckay et al. (1969) found that fistulated cattle, during the dry season in a semi-arid zone of Kenya, selected a diet with 6% and 8% CP on two sites where the average CP in the grass/browse diet was 4%. In Mali, Lambourne et al. (1983) found that the CP content of the diet selected by cattle was over 100% greater, during the 2 dry months, than that for the average hand-plucked samples. Cooper (1982), in the Transvaal, found that goats and impalas selected leaves of specific age classes from fodder WPs. The potential for being selective however very much depends on livestock
A number of feeding trials showed a negative phosphorus balance and wide calcium to phosphorus ratios, which are known to accentuate the poor performance of livestock which subsist on diets consisting of a low protein availability (Crowder et al. 1982, Richardson 1983). It is possible that the livestock at the beginning of the trials were in a good enough nutritional state that a negative phosphorus balance would not necessarily result in reduced performance and a lower intake over the short period of the trials. Longer trials may show different results.

The comparison of liveweight changes between experiments quoted in Appendix 24A is not really justified since the livestock were mostly of different age categories. Considerable variations in climatic conditions between experiments are also likely to have occurred.

The nutritional status of the livestock at the beginning of the trials may have varied between investigations and hence even a diet of a given quality would be expected to result in different liveweight responses.

Because of the lack of standardization, shortage of information and reservations concerning the methodologies followed in some of the feeding trials described in Appendix 24A, B, it is difficult to extrapolate realistically from the results to likely livestock response under field conditions.

1) Ailanthus excelsa and Albizia lebbek

These species appear to be particularly good fodder WPs. High levels of CPD and DCP and reasonable DM intake levels (at least when
fed to sheep and cattle) suggest that they are likely to be useful sources of protein supplement to low quality roughages. The intake levels of Albizia lebbek are somewhat low and this may be due to the low DMD found particularly with cattle (Fig 9.3).

Unlike the results found by Bhandari et al. (1973), with a mixed diet of Ailanthus excelsa and straw (see above), Ailanthus excelsa should theoretically provide an excellent protein supplement. Taking a midway point between points A and B in Fig. 9.2. (ie. an average DCP of 14.7 for Ailanthus excelsa fed to sheep) and assuming that an average DCP of 3 to 4 is necessary for maintenance requirements (CP level of 6 to 7%), a diet made up of 1 part Ailanthus excelsa to 3.6 - 4.8 parts of agricultural residues which have CP levels of less than 3, should be a suitable ration for maintenance for sheep. Any diet with a greater proportion of Ailanthus excelsa would contain enough DCP for production. The lack of agreement between what would be expected from extrapolations of feeding trials with exclusive diets to mixed diets compared with the actual results of trials including a mixed diet reinforces the misgivings concerning the usefulness of the results from trials with exclusive diets.

ii) Khejri

The data indicate that camels have a high capacity to digest CP from Khejri fodder, while goats appear to have an intermediate capacity and sheep a lower capacity. It appears that tannin levels may inhibit CP digestibilities, particularly in sheep, since tannin levels of points E, F and I were reported to be 2.5, 11.6 and 15% (DM) respectively. Goats, however, appear to perform considerably better.
than sheep on a Khejri diet at least in terms of CPD. Their intake levels were 64% higher (per ACU), liveweight gains were higher and they apparently obtained more energy per unit weight of fodder than sheep (Bohra 1980) (Appendix 24B; F/G). Goats also have an advantage because, for the same quantity of Khejri fodder ingested, they need less than half the water required by sheep.

It is interesting that the highest tannin levels existed in winter-lopped trees. This has led Bohra et al. (1980) and Mann (1980) to suggest that Khejri fodder collected in the summer would be better utilized than winter foliage. If this is so one has to ask why farmers have traditionally lopped Khejri in winter.

**iii) Bordi**

The results of the feeding trials indicate that camels have a higher digestibility of CP and DM than sheep and goats. Goats do not appear to digest either the CP or the DM as well as sheep, although their higher intake (per ACU) may compensate for the lower utilization efficiency. Both Bohra et al. (1981) and Ghosh et al. (1981) have stated that Bordi has a higher feed value for sheep than for goats. However, the results of a field grazing trial by Harsh et al. (1981) suggest differently. The 2 year trial was run in paddocks containing perennial grasses and Bordi bushes with an average canopy cover of 20% at the start of the trial. It showed that the production (weight gain) from goats was considerably greater than from sheep of the same age category. Table 9.2 shows that, over 2 years, goats reduced the Bordi canopy cover at the three stocking densities much more than sheep. The data also suggest that mixed grazing/browsing, with sheep and goats
together, would be more efficient at the higher stocking densities than a system with sheep or goats alone. However this trial was on a pasture with perennial grasses and it is therefore likely that the generally overgrazed areas, which have little herbaceous cover, are more suitable for goats where browse still exists.

Table 9.2. Reduction of Bordi canopy cover and weight gains of sheep and goats over 2 years on a Bordi/perennial grass pasture at three stocking densities (from Harsh et al. 1981).

<table>
<thead>
<tr>
<th>Stocking density (animals per ha)</th>
<th>Sheep</th>
<th>Goat</th>
<th>Sheep</th>
<th>Goat</th>
<th>Sheep</th>
<th>Goat</th>
</tr>
</thead>
<tbody>
<tr>
<td>% Bordi canopy reduction</td>
<td>7.2</td>
<td>62.4</td>
<td>19.2</td>
<td>81.0</td>
<td>43.2</td>
<td>90.2</td>
</tr>
<tr>
<td>Animal production (kg/ha)</td>
<td>38.0</td>
<td>79.5</td>
<td>61.4</td>
<td>105.0</td>
<td>101.0</td>
<td>129.0</td>
</tr>
</tbody>
</table>

9.1.3. Discussion and conclusion.

The results of research on the nutritional value of the better fodder WPs of W Rajasthan suggest that *Zizyphus nummularia* and *Prosopis cineraria* are not as good as *Ailanthus excelsa* and *Albizia lebbek*. It is likely that the emphasis has been placed on Bordi and Khejri because these are the traditional species and preferred in cultivated areas. It would be interesting to know why *Ailanthus excelsa* and *Albizia lebbek* are not more popular on the better sites and in the areas which receive more precipitation.
Results of species trials at Jodhpur have shown that the mean annual height increment of *Ailanthus excelsa* and *Albizia lebbek* were 170 and 108% greater respectively than that of Khejri (however the number of years of assessment for *Albizia lebbek* was considerably shorter than for the other species); the respective mean annual increments in collar diameters were 29 and 132% greater respectively (from Mann *et al.* 1984).

The evidence suggests that Khejri and Bordi can provide better than maintenance diets for camel, sheep and goats at least when harvested at certain times of year. Camels derive most nutritive benefits from Khejri and Bordi, followed by goats, particularly because of their high DM intake, and then by sheep. There is no research information on the nutritive value of Khejri or Bordi for cattle or buffalo, although local tradition suggests that Khejri foliage, at least, requires to be boiled for cattle to improve palatability and or digestibility. The extent to which this practice of processing Khejri fodder is still carried out, in view of the fuel shortage, is unclear.

Although there is some research evidence on the seasonal variation in feed value of Khejri the results do not agree with the evidence from traditional lopping practices.

The pattern of CPD, DCP and DMD in relation to the CP levels of WP fodder do not follow that which is generally accepted for herbaceous forages; this is likely to be due to compounds such as tannins and lignin which inhibit digestibility. However the short period of the trials and the uncertainty surrounding the previous feeding management of the experimental animals precludes any definite statement.
The extent to which WP fodder can actually be used as protein supplement to improve the utilization efficiency of nutrient-poor fodder is uncertain although it is likely to depend on the CPD which is specific to WP species and to livestock type. The figures quoted in Appendix 24A and shown in Figs. 9.1 and 9.2 suggest that Khejri and Bordi should at times be able to act as supplements at least to satisfy a maintenance requirement. For sheep and goats the trials indicate that the nutritive value of Khejri and Bordi in terms of CP availability is equivalent at best to a herbaceous forage with a CP content of 10% and this should sustain some growth and milk production. Some of the results of liveweight changes support this. The efficiency with which sheep are able to utilize the protein from Khejri fodder is however very variable and at times appears to be too low to meet the accepted protein requirements. For a maintenance diet which includes agricultural residues with CP values of less than 4% (ie. with DCP values of close to zero; this includes all non-legume residues), the proportion of Khejri and Bordi in the diet would need to be at least two thirds (See Fig. 9.2). However the results of the single trial on a mixed diet suggest that one may not be able to extrapolate from the relationships presented in Figs. 9.1 and 9.2. Research on mixed diets including various proportions of WP fodder would therefore be essential.

Phosphorus is generally deficient in WP fodder diets and a phosphorus supplement could make a considerable differences to the production of livestock on diets of WP fodder.
9.2. Fodder WPs on private land.

In order to evaluate the contribution which fodder WPs grown on private cultivated land can make to the fodder and fuel requirements of farm units in W Rajasthan, the model of a hypothetical farm which approaches an average farm is taken as an example and is discussed in Section 9.2.2. However first one must consider the likely densities of fodder WPs on the cultivated portion (sown area and current fallow) of farms.

9.2.1. Fodder WP densities and crop production.

It has repeatedly been stated by CAZRI researchers that Khejri trees do not reduce crop yields (eg. Mann et al. 1983), and in fact are believed to improve crop yields (Saxena 1980, 1981b, Singh et al. 1969), in particular those of pearl millet (Pennisetum typhoides) (eg. Shankarnaragan 1981). However there appear to be no published research results to substantiate the statements.

Concerning Khejri-crop mixtures, the only data available are given by Mann et al. (1983) and refer to "an estimate of Kharif (monsoon) crop production in rainfed areas of district Nagaur, under various habitats showing varying tree density (15 to 60 trees/ha) collected in sociological surveys". The methodology followed to obtain these estimates was not described and there were no tree-less plots/fields with which crop yield data could be compared. The authors purely stated that variations in grain yield "seemed more due to habitat and not the tree density". Opinion surveys of farmers have "confirmed that crops grow better under this tree" (Purohit et al. 1980). The explanation given by farmers for improved yields are leaf-fall and bird
droppings improving fertility, shade improving the crop microclimate, and shade for cattle resulting in dung concentrations under the tree canopy.

Since Khejri trees are lopped for fodder prior to leaf-fall, this is not seen as a realistic explanation. No investigations appear to have been made on the influence of scattered Khejri trees on the microclimate of associated crops. While some measurements have been made on climatic parameters in the understorey of Acacia tortilis, there is uncertainty over the size of the plots where A. tortilis occurred and the spacing appears to have been 3 x 3 m (Ramakrishna 1981) thereby making the information of questionable relevance to a situation where Khejri trees are scattered in cropland. Nevertheless, the reduction in soil temperature in the understorey is likely to be significant. In the case of the experiment with A. tortilis, the maximum temperature in the top soil zone (0.5 cm) was 10 to 16°C lower than in the open. If the improved fertility is due to cattle concentrating in the tree shade outside the crop-growing season, the higher fertility must be at the cost of lower fertility elsewhere in the fields.

The investigations which have been undertaken in Jodhpur on the effects of trees on pasture production are in some ways more relevant to the effects on crops since the site at Jodhpur is of good quality and therefore one where crops rather than pasture would normally be grown. The results of such investigations can however only give indications of the responses which crops may show since different species respond very differently as understorey plants (see chapter 2). However since the presence of trees in cropland appears to be an old
tradition, it is possible that the crop germplasm is adapted to the conditions found in such integrated systems.

Pasture yields have always been shown to be significantly better under Khejri than under other tree species such as Acacia senegal, Albizia lebbek, Prosopis juliflora and Tecomella undulata (eg. Aggarwal et al. 1976, Ahuja et al. 1978, Shankar et al. 1976 and Sharma et al. 1980). Gupta et al. (1978) found under rainfed conditions that the herbage production in the understorey of Khejri was over twice as great as under Acacia senegal and Prosopis juliflora. The differences in herbage production between the understorey of different tree species do vary between years (Ahuja et al. 1978).

Even under irrigated conditions, Shankar et al. (1976) found that the dry herbage yield under Khejri was equivalent to 2.3 tonnes/ha while the yield under Acacia senegal, Albizia lebbek, Tecomella undulata and Prosopis juliflora was equivalent to 0.78, 1.32, 1.66 and 0.85 tonnes/ha respectively. Unfortunately no investigation has been found in which comparisons were made with pasture yields on treeless sites which were similar to those on which trees were grown.

There are also problems in interpreting some of the results since tree densities between plots have not always been constant for different species (eg. Sharma et al. 1980) and Shankar et al's (1976) results referred to yields of irrigated pasture under various tree species.

A higher fertility status has been noted under Khejri compared to other tree species (see section 5.2.2); this has often been the main explanation given for the higher understorey pasture and crop yields (eg. Bhati 1981, Shankar 1981). Aggarwal (1980) suggested that the higher soil fertility status found under Khejri compared to under
Prosopis juliflora (see section 5.2.2) is due to its higher litter fall (68 g/m² p.a. and 23 g/m² p.a. respectively). Trees in these trials had not been lopped during the period of the investigation and leaf litter accumulation created conditions which are not representative of fields where trees are normally lopped for fodder. As noted in section 5.2.1 and 5.2.2, there could be other reasons why pasture yields are improved in the understorey of Khejri and the higher pasture production may itself have contributed significantly to the higher nutrient status.

The influence of Bordi on crop yields does not appear to be well documented. Purohit et al. (1981) suggested that their densities on cropland are sometimes high enough that crop yields are reduced but that this disadvantage is compensated by fodder yields obtained from Bordi during dry years. Kathju et al. (1981) also stated that Bordi's extensive lateral and secondary roots spread horizontally as well as vertically and therefore compete with other vegetation and crops for moisture and nutrients.

Data from investigations near Pali (mean P = 370 mm p.a.) on protected grazing land showed that the pasture yield was greater on plots with a Bordi canopy cover of 14% than in plots with an 18 or 11% canopy cover (Kaul et al. 1963, see also Fig. 4 in Annex I). The possibility that the grass yields were higher on the sites where the density of Bordi was greater, up to a Bordi density of 14%, could however also be due to different site conditions between plots which may themselves have led to the higher shrub canopy cover.

The evidence available does not allow one to determine what the effects of Bordi and Khejri are on crop production. It is probable
that some farmers prefer to have WP stocking densities which are detrimental to crop production because in dry years a greater forage supply is still assured.

Further it is unclear if farmers have both Khejri and Bordi on their fields in the densities mentioned in section 8.3.2, although Singh (1981) suggested that this is the case. For the purposes of this analysis three scenarios are therefore assumed: the hypothetical farm has either 50 or 100 productive Khejri trees/ha on cultivated fields; the fields also have 400 Bordi bushes/ha or none (see section 8.3.2).

9.2.2. The contribution of WPs to the fodder supply on private land.

The contribution of WPs to the fodder supply on private land is assessed by using a hypothetical farm as a working model. The long term average rainfall of the site is 300 to 400 mm p.a. The farm covers 10 ha of which 85% is currently cultivated and 10% is under current fallow. Such a farm corresponds approximately with that recommended as an "optimum sized holding" for Johdpur and Nagaur districts (Jodha 1977). 43 and 46% of farms in these two districts respectively cover 5 to 20 ha (37 and 44% are smaller than 5 ha), and the percentage of the farm which is cultivated and under current fallow is representative of the average for this size category in these districts (Jodha 1977).

Table 9.3 shows the forage production which the farmer can expect under the 4 scenarios mentioned above from fodder WPs on his land during an average rainfall year and a moderate drought year. The assumptions are that Khejri produces annually an average of 4.5 kg (DM) per tree if the tree population has a size distribution as shown in Table 8.5, and this yield is not influenced by variations in
precipitation. Each Bordi bush is assumed to produce 0.15 kg (DM) annually in an average year and 0.10 kg (DM) in a moderate drought year.

The production of agricultural residues which can be used for fodder is shown in Table 9.4. It is assumed that 40% of the sown area is planted to pearl millet, 40% to cluster bean, 15% to dew gram and 5% to green gram (see Appendix 9) and that the yields of crop residues are not reduced by the fodder WPs. The Table also includes an estimate for fodder which is available from the current fallow (1.5 ha).

Table 9.3. Fodder production from fodder WPs on a hypothetical farm according to 4 scenarios concerning WPs and years of average rainfall and moderate drought (tonnes p.a.).

<table>
<thead>
<tr>
<th>WP population/ha of cultivated land</th>
<th>50 Khejri</th>
<th>100 Khejri</th>
<th>50 Khejri</th>
<th>100 Khejri</th>
</tr>
</thead>
<tbody>
<tr>
<td>+400 Bordi</td>
<td></td>
<td></td>
<td>+400 Bordi</td>
<td></td>
</tr>
<tr>
<td><strong>Average year</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>production tonnes/ha</td>
<td>0.225</td>
<td>0.450</td>
<td>0.285</td>
<td>0.510</td>
</tr>
<tr>
<td>production tonnes</td>
<td>2.14</td>
<td>4.28</td>
<td>2.71</td>
<td>4.85</td>
</tr>
<tr>
<td><strong>Moderate drought year</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>production tonnes/ha</td>
<td>0.225</td>
<td>0.45</td>
<td>0.265</td>
<td>0.490</td>
</tr>
<tr>
<td>production tonnes</td>
<td>2.14</td>
<td>4.28</td>
<td>2.52</td>
<td>4.66</td>
</tr>
</tbody>
</table>

This estimate assumes that the land is of better quality than that of the average grazing lands and that there is some degree of control over
its grazing. The production of available pasture is assumed to be 0.5 and 0.3 tonnes/ha in an average and in a moderate drought year (see Table 8.1), i.e. 0.75 tonnes and 0.45 tonnes respectively for the farm. The quantity of pasture shown in Table 9.4 is for that which is assumed to be available during the dry period; it is also assumed that 0.35 tonnes is utilized during the monsoon irrespective of the rainfall conditions.

Table 9.4. Quantities of crop residues and pasture available from 9.5 ha of cultivated land for dry season fodder during a normal rainfall and a moderate drought year (tonnes p.a.) (see text for area sown and Appendix 9 for yields).

<table>
<thead>
<tr>
<th>Fodder type</th>
<th>Average year</th>
<th>Moderate drought</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pearl millet</td>
<td>0.96</td>
<td>0.64</td>
</tr>
<tr>
<td>(3.2 ha)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cluster bean</td>
<td>1.44</td>
<td>0.48</td>
</tr>
<tr>
<td>(3.2 ha)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dew gram</td>
<td>0.48</td>
<td>0.24</td>
</tr>
<tr>
<td>(1.2 ha)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Green gram</td>
<td>0.24</td>
<td>0.08</td>
</tr>
<tr>
<td>(0.4 ha)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pasture (current fallow)</td>
<td>0.40</td>
<td>0.10</td>
</tr>
<tr>
<td>(1.5 ha)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total forage available</td>
<td>3.52</td>
<td>1.54</td>
</tr>
</tbody>
</table>
Table 9.5 gives the total fodder which is estimated to be available for the dry season from the cultivated areas of the farm (sown areas and current fallow) according to the 4 scenarios concerning fodder WP densities and the two rainfall scenarios. The Table also gives the percentage contribution of forage obtained from the fodder WPs.

Table 9.5. Total forage available for the dry season from the cultivated areas of the farm and contribution of fodder WPs as a percentage of the total (derived from Tables 9.3 and 9.4).

<table>
<thead>
<tr>
<th>WP density scenario</th>
<th>Total production (tonnes p.a.)</th>
<th>% contribution of the fodder WPs</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Average</td>
<td>Moderate</td>
</tr>
<tr>
<td>WP density scenario</td>
<td>rainfall</td>
<td>drought</td>
</tr>
<tr>
<td>Khejri</td>
<td></td>
<td></td>
</tr>
<tr>
<td>50 Khejri</td>
<td>5.66</td>
<td>3.68</td>
</tr>
<tr>
<td>100 Khejri</td>
<td>7.80</td>
<td>5.82</td>
</tr>
<tr>
<td>Khejri + 400 Bordi</td>
<td></td>
<td></td>
</tr>
<tr>
<td>50 Khejri + 400 Bordi</td>
<td>6.23</td>
<td>4.06</td>
</tr>
<tr>
<td>100 Khejri + 400 Bordi</td>
<td>8.37</td>
<td>6.20</td>
</tr>
</tbody>
</table>
If the assumptions concerning the production of various components of the farm unit and concerning the range of possible fodder WP densities are realistic, it is quite clear that fodder WPs play a crucial role in the fodder economy of the farms. The estimated percentage contribution of WP fodder ranges from 37.8% in good rainfall years on farms which have an average of 50 Khejri trees/cultivated ha to 75.2% in moderate drought years on farms which have an average of 100 Khejri trees + 400 Bordi bushes/cultivated ha. If the assumptions concerning the proportions of crops grown are realistic, the average CP of the dry season fodder is better than that required for a maintenance diet. Assuming the value of Khejri in terms of CP availability to be equivalent to 9% CP in herbaceous forages, the average CP value of the forage available from the farm for dry season fodder is about 8.1% (DM) both for a good rainfall year and a moderate drought year in the case of a farm with an average of 50 Khejri trees/cultivated ha (see Appendix 25 for calculation).

The estimated quantity and quality of forage available from the farm, assuming a density of 50 Khejri trees/ha and a moderate drought year would provide a moderate production diet for the dry season for 2.4 ACUs (9 month dry season, maintenance diet + 10%, assuming mainly stall-fed; see section 8.4.2 and Appendix 20). However data obtained in 1961-62 by Bose et al. (1966) from a sample of 2118 households in several districts of W Rajasthan give an average of 8.04 ACUs for farms in the 6.7 to 13.4 ha size category (see Appendix 26A for assumptions and calculations). Jodha's (1980) household surveys, which refer to farms in Jodhpur and Nagaur districts in 1964-65, would suggest an average of 7.6 ACUs for farms of 10 ha (for assumptions and
calculations see Appendix 26B). It must be realised, however, that these ACU numbers per farm are averages and that there is a considerable degree of specialization in terms of ownership of various types of livestock (Bose et al. 1966). Nevertheless it is understandable that a considerable proportion of livestock owned by farmers migrate out of the area in large groups each dry season (Bose et al. 1964, Singh et al. 1979) while some livestock remain on the farm for essential day to day farm requirements.

The evidence suggests that fodder WPs make a significant contribution to the fodder available from private land for the dry season. It is clear that the number of Khejri which occur on cultivated land makes a more important contribution than Bordi and the contribution of Khejri is obviously very sensitive to the number of Khejri trees/ha. Smaller farms may be at a disadvantage compared to larger farms because they are unable to supply adequate dry season fodder for the minimum number of animals required to supply milk and draught for a farm unit. There have been suggestions that smaller holdings have higher densities of Khejri (Mitchie 1984) indicating the relative greater importance which a small farmer places on Khejri trees. Possible explanations include: small farmers are willing to accept lower crop yields in return for a certain minimum number of fodder WPs in order to maintain essential livestock in as good a condition as possible (eg. draught animals, milk buffalo); small farmers are able to protect more easily the smaller number of WP seedlings which are required to maintain a sustainable WP population structure. Under the scenario where 50 productive Khejri trees and 400 Bordi occur per ha of cultivated land the average number of Khejri trees which have to get established each year and survive until year 10 (when lopping starts - see section 8.3.1 and Table 8.5) would be
0.33/ha or 3.2 for the 9.5 ha of cultivated land on a 10 ha farm. Assuming they have to be protected until harvesting starts i.e. 10 years (see Figs. 8.3 and A.17.1), 32 trees would have to be protected each year; since this assumes that no mortalities occur, the numbers which would actually have to be protected would have to be considerably larger. The more irregular the years of germination are (e.g. due to low fruiting, low precipitation) the more new seedlings have to be protected in a year of reasonable germination.

In order to maintain a sustainable population structure of Bordi, the recruitment of this shrub would have to be an average of 8 per cultivated ha annually or 76 for the 9.5 ha of cultivated land (see section 8.3.1).

9.3. Contribution of private fodder WPs to the fuel supply.

Only Muthana (1980) and Sharma et al. (1981) appear to have published any information on branchwood yields from Khejri lopped for fodder. Muthana (1980) stated that observations on farmers' fields indicate that 2-3 kg (W) of firewood is available from the initial lopping of 8 to 10 year old Khejri trees (no information on the size of such trees was given). It would be logical to suppose that a smaller quantity of branchwood would be available from annually lopped trees compared to trees of the same size and lopped for the first time. However if the assumptions concerning increasing forage yields with age (see Table 8.5) are realistic, the annual branchwood yield would also be expected to increase.

Sharma et al. (1981) found that winter lopped Khejri trees with an average dbh of 9.1 cm had an annual wood yield of 2.78 kg
(DM)/tree (over three years) and an annual fodder yield of 0.41 kg (DM)/tree (see Appendix 13, 10 and Table A.13.3). They did not describe details concerning the lopping in their trial so it is not possible to say how representative these data are in relation to trees lopped by farmers. Unfortunately no measurements appear to have been published on branchwood yields from larger trees.

An analysis of Maghembe et al's (1983) relationship between foliar biomass and the biomass of small branches (2 cm at base) for *Prosopis juliflora* trees in different sized categories (in Kenya) has not revealed a very clear pattern, although there was a general increase in the ratio of leaf to branches with increase in tree diameter. A similar analysis of Poupon's (1976) data for *Acacia senegal* (in Senegal) has not revealed any pattern for the relationship between foliar biomass and the biomass of branches (5 cm at base).

In the absence of hard data, it is assumed for this analysis that the annual branchwood yield increases at the same rate as foliar yields (see Table 8.5) and that the average annual branchwood yield for lopped trees in the 10-20 cm dbh class is 4 kg. Table 9.6 gives the estimated branchwood yield of Khejri trees in different dbh classes and the cumulated yields over the productive life of a tree. The average annual branchwood yield over the productive life of a Khejri tree would therefore be 11 kg (DM). The annual yield of branchwood from Khejri on a farm which has an average of 50 and 100 productive trees/ha on 9.5 ha of cultivated land would therefore be 5.225 to 10.450 tonnes (DM). Further an average of 3.2 to 6.3 trees per year would reach the end of their productive life and be felled.
Table 9.6. Estimated branchwood yields (kg DM/tree p.a.) of Khejri trees in different dbh classes, estimated number of years during which trees are in each dbh category and estimated cumulated yields over the productive life of a tree (for assumptions see text).

<table>
<thead>
<tr>
<th>dbh class (cm)</th>
<th>10-20</th>
<th>20-30</th>
<th>30-40</th>
<th>40+</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yield</td>
<td>4</td>
<td>5.9</td>
<td>8.0</td>
<td>13.4</td>
<td></td>
</tr>
<tr>
<td>Years</td>
<td>5</td>
<td>10</td>
<td>15</td>
<td>100</td>
<td>140</td>
</tr>
<tr>
<td>Total (kg)</td>
<td>20</td>
<td>59</td>
<td>120</td>
<td>1340</td>
<td>1539</td>
</tr>
</tbody>
</table>

The assumption is also made that 50% of the total wood biomass quoted by Mann et al (1983 - see Fig. 8.2 and Appendix 13.5) for a Khejri tree with a 41 cm average dbh would be available from trees at the end of their productive life. That is 242 kg (484 x 50%) available from such trees would provide 0.774 or 1.549 tonnes (DM) from 50 or 100 productive trees/ha respectively. Even if one assumes that all of the wood obtained from felled trees is used for purposes other than fuel (eg. construction, agricultural implements, Malhotra 1978a, Mann 1980), and that the figures given in Table 7.1 concerning per capita annual fuel needs are realistic, ie. 461 kg, a 10 ha farm with 50 productive Khejri trees/ha would produce enough fuel for 11.3 people. Only a small proportion of households have more than 10 members (eg. 12% of households in an area of Jalore district, Bahara et al. 1964; 17.3% of households with more than 9 members in a survey of Barmer district, Malhotra 1984). Bushwood from Bordi loppings is not used for fuel but mainly for fencing material (Purohit et al 1981).
It would appear from the data presented that either the fuel problem is not as severe as has been suggested in the rural areas where fodder WPs are in the densities assumed for this analysis, or the data which have been presented are unrealistic. The smaller the farm the less the amount of fuel available from its own resources. Assuming that the average number of people in a household is 6.3 (from Bharara et al.'s 1964 data from Jalore district) the annual fuel demand of an average household is 2.904 tonnes. Assuming that the fuelwood production figures from Khejri are realistic, a farm with 4.6 ha of cultivated land would be required if all the fuel was to be supplied by Khejri and the Khejri density was 50 trees/ha. If the density was 100 trees/ha, the area of cultivated land would have to be 2.3 ha.

Considering that 37% of holdings have 0.5 to 5.0 ha of private land in Jodhpur district and 44% in Nagaur district, one can presume that the fuel shortage becomes particularly acute on small holdings and amongst the rural households which have no land (10% of "agricultural holdings" in an agricultural village of Jalore district in the early 1960's, Bharara 1964). Further there is a demand for fuelwood from the urban population (see Table 7.1) which may be particularly met by smaller farmers who are in need of cash and prefer to sell fuelwood and burn dung and agricultural residues.

9.4. Discussion and conclusions.

A number of possible hypotheses and conclusions emerge from the analysis of the fodder situation in W Rajasthan and the contribution which fodder WPs make to livestock nutrition. These hypotheses can only be regarded as provisional because of the unsatisfactory nature of
much of the data on which Chapter 8 and sections 9.1 to 9.3 were based. Nevertheless they may help to highlight the issues which should be given more emphasis and may also assist in explaining some of the developments which have taken place in the area.

The concrete evidence shows that there has been a considerable change between 1951 and 1972 in the proportion of different types of livestock (Section 7.4). Concurrently there have been considerable changes in the pattern of land ownership, of fodder resources and, consequently, their management. These major changes have a bearing on the actual and potential role of fodder WPs and on the likely success of efforts by extension services to promote their planting within the farming systems of the area. They also have a bearing on the future of the farming systems and the welfare of the population. The patterns of change in livestock types, in fodder resources and in resource ownership are clearly interrelated but for the sake of clarity are discussed separately.

9.4.1 Fodder resources.

Section 7.4 referred to the doubling in livestock densities (ACU W$_{0.75}$/ha) which is alleged to have occurred on grazing lands between 1951 and 1972, a statistic which is often quoted by Indian Researchers, even if using different livestock "Units" (eg. Jodha 1980). This increase has been due both to increases in livestock and to a reduction in grazing lands. Because of the importance, both quantitatively and qualitatively, of agricultural residues and of the likely importance of fodder WPs on private land, such an assessment is not in fact realistic since there is a considerable level of substitution in terms of fodder
availability when grazing land is converted to cropland. It would be more realistic to state that the livestock density on the grazing lands is likely to have doubled for the main period of vegetation growth when cultivated fields are out of bounds to livestock.

The effect of this increase in monsoon stocking density on the productivity of the remaining grazing lands is not documented. Interviews with various types of land users (nomads, settled agriculturalists) have suggested considerable decreases in productivity and changes in the composition of vegetation leading to fewer trees and less palatable pasture species (Malhotra et al. 1980). The likely decrease in productivity in grazing lands must be partly due to the encroachment by cultivation onto the better quality grazing lands. However the calculations in Section 8.4.2 indicate that is likely that the ground fodder component does not satisfy the monsoon fodder requirements of the livestock population.

Calculations obtained from a feeding trial with Khejri leaves in W Rajasthan, and from the proportion of the natural diet which goats and camels in N. Kenya obtain from browse, show that the average quantity of browse which the goat and camel population could consume per ha of grazing land during the 3 monsoon months is 60 to 70 kg (DM) (for calculations see Appendix 22). The average stocking density of browsers (goats and camels) on grazing lands in 1972 was 0.20 ACU/ha. Stocking densities of 0.53 goat ACUs (on a year round basis), in a trial in W Rajasthan, on a pasture of "Good Condition Class" (ie. with an average annual ground storey production of 0.9 tonnes DM/ha) have been found to reduce the canopy cover of Bordi from 20% to about 8% in two years (Harsh et al. 1981; the conversion to ACU assumed an
average weight for goats halfway between initial and final body weight (ie. 29.5 kg). Research in South Africa (Messina Research Station, mean P = 341 mm p.a.) has shown that at stocking densities estimated to have been only 0.11 Boer goat ACU/ha (on a year long basis), a 6 year trial resulted in a marked reduction in browse availability (derived from Donaldson 1979 using a conversion factor from goat numbers to ACU assuming Boer goats to weigh 45 kg, Aucamp 1978?); however no indication was given of the initial browse WP densities (Combretum apiculatum, Terminalia pruniodis, Colophospermum monplane and Grewia spp.).

Given that the majority of the grazing lands are on the poorer sites and in the drier parts of W Rajasthan, it is likely that the lower estimates for fodder WP yields would be applicable (ie. an estimated average of 2.5 kg/tree). The stocking density of fodder WPs on grazing lands is likely to be considerably lower than that which would be required to meet the possible browse demand (ie. 24 to 28 Khejri tree equivalents/ha assuming an average fodder yield of 2.5 kg/trees).

Circumstantial evidence (section 8.3.2) and the preceding discussion would suggest that the browsing pressure, resulting from the likely heavy browsing during the monsoon and browsing and lopping during the dry season, is so high that little regeneration, if any, of useful fodder WPs is likely to be taking place on grazing lands. Those fodder WPs which do get established are unlikely to grow to a size which would give the average annual foliar yields over a rotation equivalent to those assumed in section 8.3.1 (2.5 to 4.5 kg DM/tree). The high browsing and harvesting pressure may also be reducing the
annual yield of WPs as well as the life expectancy of the established trees.

CAZRI scientists have often recommended that the introduction of silvopastoral systems, including pastures and fodder WPs in intimate mixtures (eg. Paroda et al. 1980) on the rangelands is essential to increase the carrying capacity of the rangelands and help towards the economic development of W Rajasthan (eg. Ahuja 1977, Acharya et al. 1977). There are a number of problems facing the development of such systems. The capital costs of the measures which are necessary for improvement of the pastures, even for blocks of 1000 ha (see introduction to this Chapter) are high. The exclusion of goats and camels from such blocks would have to be for well in excess of 6 and 9 years respectively for the leading shoots of the fodder WPs to get out of reach of livestock unless species which grow faster than Khejri are chosen (the hypothetical height-age relationship given in Fig. A.17.2 was for trees growing on good soils with an average $P = 380$ mm p.a., soil preparation and weeding). Sheep and cattle would only be allowed at stocking densities low enough to maintain the production potential of the pasture and would probably have to be initially excluded during the dry season when browse becomes more attractive. The closure of such blocks of grazing grounds would result in greater grazing and browsing pressure outside the blocks. They would also necessitate some changes in the livestock types owned and the development of market facilities for livestock products if a cut and carry system was advocated since such a system requires a high return in cash or kind for the level of human effort spent. There would be considerable problems in the allocation of grazing and/or cut and carry rights
between all the possible claimants.

The foregoing discussion suggests that attempts to introduce improved silvopastoral systems of the types recommended by CAZRI scientist, into the grazing lands is completely unrealistic without some considerable changes taking place in people's attitudes towards common property management; considerable support from the authorities; a strong commitment by the authorities towards achieving well thought out objectives and policies (eg. fiscal, rural credit schemes) which are likely to face strong resistance.

There are misgivings concerning the value of fodder WPs on theoretical grounds. It is claimed that by providing nutritious fodder during lean periods of the year and during drought years they increase productivity (eg. Ahuja 1977). Fodder WPs enable a larger population of livestock to survive during periods of fodder scarcity compared to situations where no fodder WPs occur; hence unless the livestock numbers are controlled by human intervention, fodder WPs result in heavier stocking densities during the monsoon which must result in greater degradation of the rangelands. If they enable larger numbers of livestock to survive during years of drought, they must reduce the likelihood of the pasture component to recuperate with the return of better climatic conditions. Further if they increase the capacity of livestock to ingest low quality forage (by increasing the DCP of the diet), they must enable a greater proportion of the annual production of pastures to be ingested; this is also to the detriment of sustainable productivity. Fodder WPs may therefore have a detrimental impact on sustainable productivity in situations where livestock numbers are not controlled, rather than the increased "productivity"
suggested by Ahuja (1977) and others.

The quantitative and qualitative contribution which fodder WPs make to the fodder supply of private holdings in rainfed areas appears to be considerable although accurate assessments remain to be made concerning foliar yields particularly for larger trees and also concerning age size relationships of trees on farmers' fields. The contribution to the dry season fodder production of private holdings, in areas with an average P of 300 to 400 mm p.a., is nevertheless estimated to range from 38% in a normal rainfall year to 75% in a moderate drought year depending on the assumptions concerning fodder WP stocking densities (see Table 9.5). Qualitatively their contribution will be greater if the proportion of land planted to leguminous crops has been over estimated (see Appendix 8). The contribution which fodder WPs make to the farms' fodder production in drier areas is uncertain. A smaller proportion of land is sown to crops and under current fallow (eg. Bikaner and Jaisalmer districts in Table 9.1), more trees would therefore have to be protected for longer than for the hypothetical farm described in Section 9.2.2 (growth rates slower, greater mortalities, lower seedling establishment rate). However, the contribution which some scientist have claimed fodder WPs can make appears to be unrealistic. (eg. 1.9 tonnes DM/ha p.a. by Khejri alone, Acharya 1980 or Ghosh's 1983 statement that fodder WPs produce enough forage to meet the shortfall).

There are indications that farmers do put a high value on fodder WPs, since it appears that they sometimes accept lower crop yields in order to have more fodder WPs on cropland, and small farmers in particular apparently have higher tree stocking densities than larger
Ahuja (1977) stated that the demand for livestock products would continue to increase with the increasing human population. Table 9.7 shows the estimate which Ahuja made concerning the livestock population, the forage availability and the forage shortage between 1975 and the year 2000. These figures are "assuming a yearly increase in livestock population at 2% and the forage production at 3% and 2 years out of 5 years as scarcity years in the arid regions". It would be more realistic to substitute "potential production" for "forage availability". It is also felt that the scenario which Ahuja (1977) proposed and which has been repeated by other authors is completely unrealistic as there is little evidence of improved fodder production except in areas where dry land farming is converted to irrigated farming.

Further improvements in forage production are likely to come primarily from privately owned land. The greatest contributions could be made as more land comes under irrigation and, on private rainfed land, with the uptake of pasture cultivation in intermittent strips with food crops (which may not necessarily result in lower crop yields (see Section 8.2.). The contribution of fodder WPs to the farms' forage production could be increased by choosing faster growing provenances of the indigenous WPs (assuming that a faster growth is not at the expense of foliage production), such as Khejri (eg. Mann et al.). The selection and breeding of WP germplasm which has lower levels of digestive inhibitors (eg. tannin in Khejri) is being undertaken (Muthana 1983) and this should improve the nutritive value of the fodder. However other problems may follow such as a
Table 9.7 Estimated livestock population and forage supply and demand 1975-2000 (from Ahuja 1977).

<table>
<thead>
<tr>
<th>Year</th>
<th>Adult cattle unit (ACU)</th>
<th>Forage in million tonnes (?DM)</th>
<th>Forage shortage %</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Needs</td>
<td>Availability</td>
</tr>
<tr>
<td>1980</td>
<td>7.405</td>
<td>18.571</td>
<td>11.693</td>
</tr>
<tr>
<td>1985</td>
<td>8.146</td>
<td>20.366</td>
<td>13.316</td>
</tr>
<tr>
<td>1990</td>
<td>8.961</td>
<td>22.400</td>
<td>15.466</td>
</tr>
<tr>
<td>1995</td>
<td>9.858</td>
<td>24.645</td>
<td>17.785</td>
</tr>
<tr>
<td>2000</td>
<td>10.834</td>
<td>27.085</td>
<td>20.159</td>
</tr>
</tbody>
</table>

Note: 1/ For conversion factors to ACU used by Ahuja (1977) see note 4 in Appendix 7a.
greater susceptibility to insect defoliators. The evaluation of the suitability of growing other indigenous and exotic species, which are more productive and of better quality (e.g. *Ailanthus excelsa* and *Albizia lebbek*), with crops should be undertaken. The careful choice of species is essential; for instance although the performance of *Acacia tortilis* is particularly good, it is unpopular with farmers because of its spines. Such an evaluation should aim at determining the highest tree stocking densities which do not lead to reduced crop yields and the optimum spacial arrangement of the tree component (e.g. row orientation). It would also be important to examine the trade off which occurs between increasing the WP densities, thereby obtaining a higher dry season forage production and reduced crop yields and how the influence of WPs on crop yields varies with annual fluctuations in precipitation. In irrigated areas, the introduction of more productive fodder WPs such as *Leucaena leucocephala* and *Gliricida sepium* would be valuable.

The use of tractors for ploughing has apparently considerably reduced the fodder WP stocking densities on cropland. An evaluation should be made of the relative merits of reduced fodder demand resulting from tractor ploughing (reduced draught animal power) against reduced fodder and dung supply.

9.4.2. Livestock trends.

Changes in both livestock numbers and in the proportion of different livestock types occur as a result of a number of factors such as changes in fodder resources, changes in the relative value of various livestock products and functions and also in the relative rates
of mortality and reproduction. To conduct a thorough analysis of the livestock trends between 1951 and 1972 an understanding of the impact of all these factors and their interactions within the various farming systems of W Rajasthan would be required. Furthermore changes which have taken place in the fodder resources outside the area on which the livestock depend also affect livestock in W Rajasthan and would have to be considered. Unfortunately, such detailed information does not appear to be available but some possible explanations for the observed trends can nevertheless be made.

While the livestock numbers increased at an annual rate of 2.5% between 1951 and 1972, the numbers of ACUs increased by only 1.7% annually (see Fig. 9.4). The years preceding both census years had precipitation levels which were well below normal. It is difficult to know what the long term trend in ACUs actually is because of the great short-term variability in precipitation levels. Nevertheless between 1961 and 1972, following a number of poor rainfall years, the livestock numbers had increased by 1.45% annually whilst the ACU numbers had actually dropped. This should be compared with Ahuja's (1977) suggestion that livestock ACU's will increase at an annual rate of 2% until the year 2000 (Table 9.7).

The explanation for the difference between trends in livestock numbers and ACUs lies with change in the proportions of livestock types. It could be argued that the considerable increase which has occurred in goat numbers resulted from increased demand for goat meat from major cities in the N.W. of India and from the Middle East. Data on this demand and prices paid for goats are difficult to obtain as a considerable proportion of the export is smuggled into Pakistan (Ghosh
Fig. 9.4 Trends in livestock and ACU numbers from 1951 to 1972 in W. Rajasthan.
1983). However it is believed that this is not the only explanation. During drought years in rainfed areas goats survive better than cattle, buffalo and sheep. In an area of Jodhpur district which receives an average rainfall of 190 mm p.a., the numbers of livestock dropped by 19.7% between 1961 and 1966 due to drought years but by 1972 had increased to the 1961 levels. During those 11 years, the cattle, buffalo and sheep numbers decreased by 49.8%, 61.9% and 4.4% while goat and camel numbers had increased by 34.8 and 38.5% respectively (Bharara 1980). The area concerned has an average sown area of 53% resulting in a considerably greater dependence on common grazing grounds for livestock fodder than for the hypothetical farm described in sections 9.2 and 9.3.

Goats and camels appear to be more successful than other livestock in years of drought and in degraded environments. The lower mortality during drought years and the better success of small stock in degraded habitats, where perennial grasses are disappearing as a result of grazing pressure, has been observed in other regions such as in some of the Maasai areas of Kenya where goats are preferred by poorer households (eg. King et al. 1984).

It is of interest to examine the relative success of goats compared with sheep in such environments; it appears to be due to a number of factors:

i) lower overall water demand of goats (Devendra et al. 1982, Ghosh et al. 1980);

ii) lower water demand per unit of WP fodder (eg. Khejri) ingested by goats (Bohra 1980; see also Section 9.1.2);

iii) higher browse intake by goats during the dry season, reducing
dependence on drinking and increasing nutrient intake and absorption (see Section 9.1.2); 

iv) reduction of feed intake when deprived of water is less in goats;  
v) goats tolerate higher levels of salt in drinking water (Ghosh et al. 1980).

The result is that goat liveweight gains have been shown to be greater on fodder WP diets which partly explains their relatively higher reproductive rate. Goats kid on average once a year, but Bose et al. (1964) suggested that at least in some areas ewes "lamb once in about two years". In comparison the calving rate of cattle is less than 40% and that of buffalo about 50% (Crotty 1980). Furthermore although first calving in well fed cows and buffaloes takes place at about 4 and 5 years respectively, under-fed cows and buffaloes calve, on average, one year later (Bose et al. 1966). Whilst camels can withstand harsh conditions most easily, economic studies in Rajasthan have shown that goats are "130% more economical than cattle and 123% more economical than sheep" (Ghosh et al. 1980). Similar conclusions concerning the relative productive advantage of goats over sheep and cattle in degraded semi-arid areas particularly where browse occurs are presented by Carles (1981), Le Houerou (1980) and McCammon Feldman et al. (1981). Further advantages of goats are that they are also valued in W Rajasthan for their ability to act as foster mothers for lambs whose mothers have died or do not produce enough milk (Bose et al. 1964, Malhotra 1984), and they provide milk for human consumption especially by poorer families.

Between 1961 and 1972, the buffalo population in the area increased by 14.6%. This is likely to be due to increases in irrigated
cropland, resulting locally in better fodder supplies (Acharya et al. 1977), and to an improved marketing structure for their products (Mruthyunjaya et al. 1984).

The extent to which the demand for bullocks has been reduced because of tractor ploughing and camel ploughing does not seem to be documented although the number of tractors had increased dramatically from 240 in 1951 to 6694 in 1972 (Purohit et al. 1984).

Thus it is suggested that the increase in livestock ACUs which Ahuja (1977) estimated will take place by the year 2000 (see Table 9.7) is unrealistic because the fodder supply is not likely to increase at the rate he suggested. A lower number of ACUs combined with other technological developments (eg. tractor ploughing) may theoretically result in the increased demand for livestock products and functions (see Annexe I) being met; an increase in demand for livestock products will develop with the rise in human population.

The importance of the contribution of livestock to the supply of nutrients to croplands through manure application is uncertain. In many areas of the world, the rangelands and forests are grazed during the day time and during the fallow season are tethered at night in cropland resulting in a shift of nutrients from the commonlands to private land. Wyatt-Smith (1982) found that 2.8 ha of pasture and forest land were required to feed livestock associated with each ha of cropland on farms in west-central Nepal. By contrast two separate studies in the Kumaun Himalayas (Pandey et al., 1984; and Singh et al., 1984) have suggested that the area of forest/grazing land required to provide fodder to support each ha of cropland is 9.3 ha and 18 ha respectively. The equivalent area available for most districts of W Rajasthan is considerably lower.
than 0.5 ha (see Table 9.1). In the past, in W Rajasthan, it appears that the contribution of dung to cropland from livestock feeding on common rangeland may have been important (eg. Malhotra et al. 1963). However with the shortage of dry season grazing area in the early 1970's, made worse by the likelihood that its production is likely to have been largely consumed during the monsoon, the major contribution which livestock can make to the fertility status of the crop lands is by converting agricultural residues to more easily degraded dung (eg. Bose et al. 1964) - ie. reducing the C/N ratio of the organic matter already produced on the cropland. Hence the fertility status of the croplands must be declining unless artificial fertilizer inputs are increasingly compensating for the export of nutrients from the sites in terms of grain. This effect would be particularly severe in irrigated areas where the cropping intensity is higher.

9.4.3. Wood requirements.

It is generally accepted that the discrepancy between the supply and demand for wood products in W Rajasthan is getting greater. Section 9.3 suggests that if the assumptions made concerning the fuelwood production from Khejri harvested for fodder are realistic, a small to medium sized farm (c. 5 ha) in the 300-400 rainfall zone should produce enough fuelwood for the average household with a Khejri density of 50 trees per ha of cultivated land. Sociological surveys do not clarify the situation enough to identify (quantitatively or qualitatively) which wood products originate from which sources (eg. common land, private land, market place). There is also the problem that questions related to fuel demand and supply do not distinguish
between wood, dung and agricultural residues.

Bharara et al. (1970) found during sociological surveys in Pali district that although 56% of households met their fuel requirements from their own fields, 83% still claimed to experience a fuel shortage and even those who reported no fuel shortage used cow dung extensively as fuel. Bose et al. (1965) in a survey of Barmer district found that 90% of households collected fuel from their own fields but only 47% collected from common lands.

It appears that wood for agricultural implements is in particularly short supply. Acacia nilotica and Tecomella undulata are preferred species for these purposes and Bose et al's (1965) survey of Barmer district found that whilst 46% of households obtained the wood for agricultural implements from their own land, 60% purchased wood for this purpose in the market. They also found that the villagers' first preference concerning choice of species for planting was for those supplying wood for agricultural implements. However there was no indication of the densities and species composition of trees already on the farmers' land. Hence it is not possible to know if the ranking of preference for various products from trees took into account the trees which they already owned. Further, although the survey indicated "a stong desire to plant trees", most farmers had not planted trees on their land in the 3 years prior to the survey because of "the belief that on account of drought conditions trees even if planted would not survive" (Bose et al. 1965). It is possible therefore that the wish for trees to be planted for agricultural implements was in the hope that it would be carried out by the Forest Department on government land. A similar response concerning
preferences for species supplying timber for agricultural implements (and shade) was found by Bharara et al. (1970) in Pali district, although only 8% of households had planted trees during the previous 3 years, and only a very small percentage of those planted had a use for agricultural implements. The estimated average annual requirement per household for timber for "agricultural implements, housing, household articles" was estimated to be 150 kg by Bose et al. (1965) in Barmer district. In Nagaur district however, Malhotra et al. (1980a) stated that the average annual requirement per household ranged (in different areas) from 3.2 tonnes (?W) to 5.9 tonnes (?W) for agricultural implements alone.

9.4.4. Resource ownership and socio-economic development.

An appreciation of resource ownership or resource utilization rights is essential if the interactions and developments of the various production components of farming systems is to be understood. Such an understanding is an essential prerequisite for the evaluation of alternative policies, and for the formulation of social and physical development plans. This includes the impact which agro-silvopastoral developments may have in W Rajasthan and particularly the identification of situations in which they are likely to be successful. However it is outside the scope of this thesis to deal with the subject in depth. Furthermore, a shortage of detailed information seems to exist for W Rajasthan concerning the relationship between the three main resources — cropland, common property range land (CPRL) and livestock, and concerning the way in which this relationship varies both for farm units which depend on different proportions of these resources.
and for different areas of W Rajasthan.

Jodha (1980) has argued that the land reforms, which abolished the tenurial arrangements of the feudal system around 1950, have contributed considerably to the decline of the productivity of the natural resource base. The cost to the farmer of cropping decreased more than ten-fold between 1950-51 and 1964-65 (at 1976-77 prices). Grazing fees were abolished with the land reforms. Concurrently the price of wool and ghee increased several fold (at 1976-77 prices) and an efficient milk marketing system has developed since 1973 (Mittal 1980). The improved marketing and transport facilities, and for some commodities the reduced reliance on middle men, have increased the returns to the producers. Hence, the cultivation of submarginal land has become more profitable and investment in livestock has "accentuated the rate of exploitation of an already deficient and fast-depleting resource base" (Jodha 1980). The reduced isolation of the area has also ensured easier access for relief supplies during drought years resulting in increased pressure on land after the years of shortage (Jodha 1980). Insurance against risk in terms of livestock production has been achieved on CPRLs by increasing the herd size.

However, there appears to have been some diversification in production since the early 1960s. Jodha (1980) reported on studies which were carried out in 1965 in the districts of Jodhpur, Jaisalmer and Nagaur. 78% of households engaged in cultivation in Jaisalmer were not cultivators prior to 1954, 36% of households in Nagaur which were involved in sheep and goat husbandry had not been so and 19% of households engaged in dairying in Jodhpur had not been so prior to 1954. Animal husbandry was adopted by wealthy land owners to
compensate for land lost when the land ceiling regulations were introduced (Gupta 1971).

In surveys of 2118 households in Barmer, Sirohit and Jalore districts, Bose et al. (1966) found that the number of livestock was directly related to the size of holding. Table 9.8 shows the average number of livestock belonging to households of various land holding size. The holdings in areas which are drier are on average larger and it could be argued that it is in such areas that livestock husbandry is of greater relative importance thereby explaining the positive correlation between holding size and livestock owned. However similar relationships have been found within a small part of Jodhpur district (Kalla et al. 1972) suggesting that larger holdings, irrespective of climate, may be associated with the ownership of a larger number of livestock. The exception is for nomads and semi-nomads who may not have rights to any land and yet own herds of considerable size.

Considering that the CPRLs have been shrinking and deteriorating, the fact that under private control land can produce fodder from agricultural residues as well as the chance of a crop in the occasional good year, the attraction of private control over land management and utilization is particularly strong.
Table 9.8. Average ownership of livestock by rural households of different sizes in W Rajasthan (from Bose et al. 1966; based on a sample of 2118 households in 3 districts during 1961-62).

<table>
<thead>
<tr>
<th>Size of holdings (ha)</th>
<th>% No. of holdings</th>
<th>Bullocks</th>
<th>Cows</th>
<th>Buffaloes</th>
<th>Camel</th>
<th>Sheep</th>
<th>Goats</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>9.5</td>
<td>0.17</td>
<td>1.56</td>
<td>0.37</td>
<td>0.36</td>
<td>0.81</td>
<td>2.09</td>
</tr>
<tr>
<td>0-6.7</td>
<td>32.8</td>
<td>1.35</td>
<td>2.40</td>
<td>0.65</td>
<td>0.15</td>
<td>5.37</td>
<td>3.60</td>
</tr>
<tr>
<td>6.8-13.4</td>
<td>22.4</td>
<td>1.84</td>
<td>2.94</td>
<td>0.82</td>
<td>0.33</td>
<td>4.81</td>
<td>4.84</td>
</tr>
<tr>
<td>13.5-17.1</td>
<td>14.6</td>
<td>1.88</td>
<td>4.04</td>
<td>1.09</td>
<td>0.37</td>
<td>4.16</td>
<td>4.02</td>
</tr>
<tr>
<td>17.1</td>
<td>20.9</td>
<td>2.30</td>
<td>6.50</td>
<td>0.91</td>
<td>0.58</td>
<td>5.72</td>
<td>7.27</td>
</tr>
</tbody>
</table>

Socio-economic surveys of rural households of 3 districts in W Rajasthan have shown that landless labourers and small farmers obtained 42% of the household's gross income from CPRLs while the corresponding figure for large farms was 15% (Jodha 1984). Table 9.9 shows the extent of the reliance of labourers, small farmers and large farmers on the CPRLs. Large farmers appear to rely on their own lands for their fuel supply. However Table 9.9 does not refer to the nature of the fuel. Bharara et al. (1970) found that a greater proportion of smaller farmers had planted trees than larger farmers (>20 ha).
Table 9.9. Indications of dependence on CPRLs by different categories of rural households in selected villages in Rajasthan (from Johda 1984).

<table>
<thead>
<tr>
<th>Labour, Small farmer</th>
<th>Large farmer</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of households</td>
<td>58</td>
</tr>
<tr>
<td>% of households</td>
<td></td>
</tr>
<tr>
<td>- meeting 70% grazing requirement from CPRLs</td>
<td>97</td>
</tr>
<tr>
<td>- collecting food material from CPRLs</td>
<td>41</td>
</tr>
<tr>
<td>- collecting fuel from CPRLs</td>
<td>86</td>
</tr>
<tr>
<td>- collecting fodder from CPRLs</td>
<td>36</td>
</tr>
<tr>
<td>- getting supplies and wage employment on CPRLs during drought</td>
<td>69</td>
</tr>
<tr>
<td>- CPRL based income as proportion of per household gross income (%)</td>
<td>42</td>
</tr>
</tbody>
</table>

The ability of the rural poor to survive in India has relied in great part on the services which they performed for the wealthier sectors of society and on the scavenging rights which they have traditionally had on land managed by the relatively better off. Das Gupta (1984) has shown how the impact of over-crowding and the shrinkage of resources has inevitably shifted onto the poor. For instance in a village in a state of N.E. India, dung could
traditionally be collected by anyone from the village streets; however by 1950 "the competition for this resource had become so intense that the village council legislated that the dung belonged solely to the owners of the cattle".

No detailed information is available on the extent to which smaller herd owners and smaller farmers can afford to split family labour in order to migrate seasonally in search of dry season fodder. It may be that the poorer sectors of rural society have less flexibility in terms of choice of CPRLs than larger owners whose resources can give them access to more reliable dry season rangelands. Bose et al. (1966) stated that it was particularly households owning larger flocks which migrated to more favourable grazing areas elsewhere in Rajasthan or outside the State.

The appropriation of further CPRL for private use, by legal and illegal means, has been found in Nagaur and Jodpur districts to be, in about 61% of cases, by farmers who already possessed 10 ha or more (Jodha 1984); the proportion of the land going to the landless category was 11 to 13%. Further, of the land which was acquired, 90% of the "good quality" land went to the larger farmers. The government often acquires additional revenue by auctioning the more productive CPRLs to contractors; once these are degraded and fail to attract further tenders they are returned to public use (Jodhur 1984).

There appears to be increasing resentment from settled agriculturalists towards nomadic herdsmen. Their past importance in trading has been superseded by improved transport facilities; they are perceived as being responsible for damage to crops and for reducing the already scarce grazing resource (Malhotra 1984).
The degree of indebtedness may reduce the choice of resource management options available to farmers and consequently their ability to improve the sustainability of their production system. Indebtedness is widespread in W Rajasthan. No information appears to be available concerning the relative frequency and magnitude of indebtedness between farmers with holdings of different sizes, but it would be reasonable to suppose that the smaller the farmer the greater the extent of indebtedness. Loans are obtained particularly in years of high livestock mortality or of crop failure (Bose et al. 1964, Malhotra et al. 1966). Further considerable loans are procured for socio-religious purposes. The extent of indebtedness has been found to be more significant amongst pastoral nomads (Malhotra 1978). The traditional source of borrowing has been the money lender who charges a minimum of 24% interest rate annually (Malhotra et al. 1963). The extent to which this has been replaced by institutional sources of borrowing has been minimal (Malhotra 1978).

In some other areas of the world, the poorer sectors of society derive a greater contribution to their livelihood from livestock than the richer farmers (eg. Conlin et al 1979, Gautam 1983, for Nepal). This is made possible because of the relatively large area of CPRL to cropland. In W Rahajasthan, however, the extent to which a household can obtain livestock products may be directly proportional to the amount and quality of land cultivated as this is where controlled production of dry season fodder is possible. In a survey of households in an area of Jodhpur district, Kalla et al. (1972) found that the return on investment in livestock was proportionately lower amongst
small farms compared to larger farms. For the particular year of their investigation, the returns on investment in livestock by small farmers were actually found to be negative due to poor rainfall.

It would appear that the benefits of agro-silvopastoralism are on the whole proportional to the amount of land over which a farmer has private control. Further, because of the greater dry season fodder resources at his disposal, the larger farmer may be able to take more advantage of the common grazing grounds. Part of the herd can also be moved during the dry season to better grazing areas if there is sufficient flexibility in the farm unit but poorer households have considerably less flexibility and are therefore less likely to be able to use this tactic.

9.4.5. Research.

It is very sad and unfortunate that after nearly 30 years of research on various aspects of agro-silvopastoralism it is still not possible to draw firm conclusions from the results. There are a number of reasons for this.

1. Some of the research has been of very poor quality: not comparing like with like (e.g., comparing the quantitative effect of different treatments on trees which differed in size before the start of the trials); no control treatments against which the results of the treatment plots can be compared (e.g., the effect of trees on pasture production without a tree-less control); no details concerning the size of trees from which yields are quoted; no record of past management regimes of trees or plots.
2. Some of the research may have been properly conducted but the methodology is described in an ambiguous way so that one does not know to what the results refer (e.g., foliar yields from trees rested for 3 years being the yields at year 3 or the average annual yield from trees lopped every 3 years; no reference to the season of foliar sampling for feeding trials).

3. Much research has been irrelevant in terms of the significance of the results to the real situation in the field. This has been the case all the way from the parameters measured on individual plants through to the choice of production systems to investigate. For instance it appears that estimates of foliar yields have sometimes been derived from trees which may never have previously been lopped; such results are therefore completely unrepresentative of the actual yields which trees would produce on an annual basis. All research examining the interactions between trees and pasture appears to have been carried out on sites which are of good quality which would not be under pasture outside the research station; it is not reasonable to extrapolate from the relationships which occur on good sites between the tree and understorey component to what is likely to happen on poorer sites. The results of feeding trials based on exclusive diets of one fodder WP species are likely to give an inadequate indication of the actual nutritional value of that WP species under field conditions when it forms only part of the diet. Researchers are investigating the possibilities of selecting more palatable and digestible fodder WPs, such as Khejri with low tannin contents. Such WPs would only be of any value on land where strict grazing control can be implemented. For common rangelands, it might be advantageous to select species and
germplasm with foliage of lower palatability but a higher production of palatable and nutritious pods (eg. *Prosopis juliflora*).

5. A number of evaluations of the likely functioning of systems are based on information from other sources which has been uncritically accepted.

6. The explanations given for responses which have been found to occur in agro-silvopastoral systems have often been unsatisfactory. The range of possible factors which are at play in the complex interactions have seldom been investigated in detail. This can lead to completely erroneous conclusions.

If it is felt that research on agro-silvopastoral systems is likely to be of benefit to W Rajasthan's development, the inadequacies of the published work suggests that much research may have to be redone. However it is possible that the experiments themselves were well done and that it is only the analysis and presentation of data which are lacking. If this is the case, considerable time and resources could be saved by re-examining the original data and experimental information. A critical appraisal of the results of previous research and of its methodology is always required. Results of poor research may lead to further research being undertaken which would otherwise not be initiated if the true nature of the initial results was known. On the other hand some of the original research may nevertheless help to identify promising avenues for further investigation and may also help to narrow the limits within which an
investigation is likely to be worthwhile (eg. spacing trials).

Whilst the results of research station trials can be of considerable value to test hypotheses, they are only of any real value if the results have utility for practitioners and policy makers. In the case of W Rajasthan there is a dire shortage of information to help planners and decision makers to identify the factors determining the development of farming systems. It is only with such knowledge that appropriate remedial measures can be introduced to influence the direction and nature of development.

To be of any real value future, research should take realistic account of farmers' perceptions and constraints. These will vary between sectors of communities and in different areas. Results of such research could then be used to develop an understanding of resource management methods, their potential and their implications.

9.4.6. Conclusions.

The contradictory nature of many of the claims made concerning the development and potential production of the natural resource sector in W Rajasthan can be attributed to the very unsatisfactory nature of the information available. This has in some cases led to the misinterpretation of results derived from situations which had little in common with the situation for which the data were applied.

There are indications, but no proof, that agro-silvopastoral systems have advantages over single production systems in certain situations and on certain specific sites. Research results hint at the possibility of understorey production not being reduced by the presence of certain WP species, at least up to certain levels of WP densities,
and of perhaps even being improved. Sociological surveys support the suggestions made by research and further, indicate that farmers on private land may be prepared to accept a reduction in uncertain crop yields for a greater and more secure source of dry season fodder.

Fodder WPs on CPRLs have clearly been an advantage to individual livestock owners in buffering the impact of recurrent drought on animal production. This, combined with the reduction of the cost of grazing in the early 1950s, has resulted in a shrinking, and a degeneration, of the grazing resource, partly as a result of forage availability from WPs. This degeneration has in turn contributed to a change in livestock types which are better adapted and more productive on degraded rangelands where an increasing proportion of the green biomass is contributed by less palatable herbs and WPs. However, calculations indicate that the resulting increase in browser density is likely to lead to a situation where only the least palatable herbaceous plants and WPs get established and regenerate.

There has been a significant increase in the net value of crop production which has pushed cultivation onto the better grazing lands which are mostly sub-marginal for cropping. This is resulting in a considerable decline in the productive potential of the sites due to wind erosion and a lowering of soil fertility. Concurrently, because of the reduction and degradation of the grazing resource there has been considerable attraction in having private control over dry season forage availability to which fodder WPs can contribute considerably. There are indications that smaller land holders place an even greater importance on private fodder WPs than larger land holders; this is understandable since with the reduction in the CPRLs they are having to
produce an increasing proportion of their own fodder needs.

Claims made concerning the desirability and necessity of developing silvopastoral systems on CPRLs including pasture improvements associated with palatable fodder WP plantings, are completely unrealistic given the socio-economic conditions of W Rajasthan. In order to succeed, they would require conditions of management control the lack of which has been the very reason for the degradation which exists at present. To claim that such developments would be sustainable is, on past evidence, both dishonest and misleading. Sustainable increases in production and socio-economic development, implying considerable changes in the way common resources are shared out between people of different socio-economic status, are only achievable if the livestock densities are commensurate with the long term carrying capacity of the land.

There is considerable evidence that the wealthier sectors of rural society are increasing their private usufructuary rights over the better CPRLs leaving the less productive land to provide an increasing proportion of the livelihood of the poorest sectors of society. The nomads and semi-nomads have largely lost their income from trading and have a reduced grazing resource to rely on. Hence the flexibility in management which is necessary for the establishment of silvopastoral systems is further reduced. Two major factors influencing the future development of the rural sector of W Rajasthan will be increases in irrigation and in mechanization of land preparation. Further an increase in the proportion of hybrid cattle and buffalo in the bovine population would help improve productivity. The importance of hybrids between *Bos indicus* and *Bos taurus* are that *Bos indicus* cows lactate only when calves are at foot (ie. no culling of calves is possible even if
taboos against slaughter are removed) whilst Bos taurus and hybrids lactate without a calf at foot (Crotty 1980). However buffalo and hybrid cattle appear to require better fodder.

Further hopes lie in improved rural credit schemes which may help reduce the dependence on traditional money lenders to which a large proportion of rural society are continually in debt, and in improved product collection and marketing structures for animal products, which would encourage higher productivity per animal rather than larger herd sizes. The development of a dairy industry, largely to serve the urban centers such as Delhi (Mittal 1980), is particularly encouraging as it also reduces the need for fuelwood which is required for the traditional processing of milk into ghee. In other parts of India, and in particular Gujarat, improved milk production has generally resulted in increased productivity on the rest of the holding (eg. Brumby 1981, and see section 1.3.1). Improved forage production on cropland resulting from the introduction of grass strips which may not reduce crop yields and which reduce soil erosion losses, combined with selection for the more productive and more palatable fodder WPs which are most complementary to crop production would also improve the productivity of farms. The fertility of the cultivated lands will, however, continue to drop if present practices continue since the proportion of grazing land to cropland is so low.

Finally, all the above measures by which production may be improved can only help to buy time, they are not long term solutions. Thus the fundamental problems of over-population and increased pressure on the land resources must be tackled by politicians and administrators, even at the risk of short term unpopularity.
PART III
CHAPTER 10

Discussion and Conclusions

Chapters 2 to 5 have described the numerous ways in which trees and understorey plants interact and the ways in which livestock respond to the influences which trees can have on microclimate. The nature of the responses of the various components of tree-pasture-animal systems are qualitatively and quantitatively highly variable. The variability results from the highly specific nature of the interactions in terms of the sites and their fluctuating diurnal and seasonal characteristics; the species and ecotypes (breeds or provenances) of the 3 components, their spatial distribution and frequency and the seasonal variability of their influences on and responses to specific factors (eg. temperature, light, wind, soil moisture and nutrients, allelochemics, canopy interceptions, depth of water table) and of their interactions. The value of trees in heat or cold stress alleviation in livestock is made even more variable by the ability of livestock to reduce the amplitude of the temperature stress in a number of ways.

The benefits of integrated tree-pasture-animal systems can be measured in terms of physical production, sustainability of production, financial profitability, economic efficiency, risk minimization, and in terms of the impact on management (eg. efficient use of labour) of the farm unit.
10.1 The indirect role of trees in livestock production.

Trees can lead to a considerable improvement in livestock production, or at least to a lower reduction in production, by reducing heat and/or cold stress. The ways by which these benefits occur may be subtle and go unnoticed by farmers (e.g. reduced early embryo death). The benefits may be direct in terms of livestock response or indirect in terms of lower costs relative to alternative ways of achieving the same level of production (e.g. lower levels of supplementary feeding during cold periods). However the appropriate location of trees within the farm unit, appropriate management of trees individually and in groups, and appropriate management of the herd are essential to obtain maximum benefits. Indeed trees may with appropriate management be beneficial to livestock conditions, but on the same farm unit may inadvertently result in lower animal production compared to a similar farm unit which has no trees. This could happen if the trees are not located in the right place (e.g. too close to water resulting in a higher incidence of disease), not of the appropriate shape (e.g. low lying branches promoting tsetse infestation – see Annexe I, Goldson 1973), or if the herd is not managed appropriately (e.g. moving the stock away from shelterbelts at a time when snow trapping may result in smothering sheep).

Livestock can also reduce temperature stress directly by behavioural means (e.g. grouping together in cold winds) or by choosing locations in the topography where the stress load is reduced (e.g. sheltered from cold winds by a hillock or from long wave radiation loss by a rock overhang, or alleviating the heat load by standing in a windy spot). They can also do so indirectly by eating more to generate more
heat thereby being able to maintain their physiological status under colder conditions; they can also withstand higher heat loads through increases in evaporative heat losses by drinking more. The relative value of trees in heat and cold stress alleviation therefore also depends on the alternative means of stress alleviation on any site and on the sensitivity of the livestock production component (liveweight gain, milk production, reproductive rate) at any one time.

10.2 Livestock and forest production.

Although the subject has not been discussed in the context of W Rajasthan, livestock can be used to benefit forest production in a number of ways. A concentration of high livestock densities at the appropriate time (in terms of seed year, seeding time and germination) has in many parts of the world resulted in increased natural regeneration of trees by improving the seed-bed (eg. Hjort 1965 with Pinus ponderosa in the USA, Whyte (1957) for several species in India). Livestock have also successfully been used to prepare forest planting sites (eg. Beveridge et al. 1973 and Walton 1972 for Pinus radiata in New Zealand), and to weed young plantations resulting sometimes in significantly better tree growth and generally in reduced fire risks (eg. Adams 1975, Bell 1981 and Gregor 1972 for Pinus caribaea var. hondurensis, Barr. and Golf. in Fiji, Caquet 1980 with Pinus maritima in S.W. France). Access to the stand can be improved and reduce the cost of silvicultural interventions such as thinning and pruning (eg. Knowles 1973 for Pinus radiata in New Zealand). Although such benefits have been found to be considerable in some situations, the timing of the introduction of livestock, their stocking density, type,
age and nutritional status, and the ability to remove livestock as soon as damage starts to occur to the soil and the roots or to the aerial parts of the trees, have all been essential conditions of success. Hence there are situations where not only forest production benefits from livestock grazing, but there is simultaneously the opportunity for some fodder contribution to the livestock production sector. However, without appropriate grazing control, the benefits can easily turn into considerable losses compared to sites where livestock have not had access. The need to be able to remove livestock from the forest area for a number of years after establishment until the aerial parts of the tree cannot be damaged and, subsequently during times of year when the soils may be particularly susceptible to poaching or when bark stripping starts to occur, requires that the livestock owner has both the ability for considerable forward planning and considerable flexibility in terms of alternative fodder supplies. Alternatively the value of fodder to the adjoining farming systems is so high that a cut and carry system is attractive. This flexibility is also necessary in situations where the objective of the trees is primarily to indirectly improve livestock production; livestock have to be removed from woodland shelter when the poaching is such that the continued existence of the woodland is jeopardized (see Section 6.1.2).

10.3. Integrated forestry, pasture and animal production systems.

It should be clear from chapters 2, 4 and 5 that the nature and amplitude of the interactions between tree and understorey components or of the effects of strips of woodland on adjoining pasture are likely to be highly variable; this is reflected in the evidence from a number
of studies which show negative or positive interactions.

10.3.1. Trees and pasture production.

A number of studies have shown a considerably reduced production of pasture when in association with trees, even at very low tree stocking densities, compared to tree-less sites. Beale (1973), in S.W. Queensland, found a rapid drop in herbage production with basal area increases of Acacia aneura F. Muell. from 0-1.5 m$^2$ (see Fig. 5 in Annexe I) indicating that even a few trees reduce pasture production considerably. Walker et al. (1972) found in S. Queensland that maximum levels of herbage production were obtained if no more than 6 mature Eucalyptus populnea trees were left per ha. Such results have led some pasture scientists to propose that trees should generally be cleared from pasture land (eg. Ward et al. 1964, Whiteman 1980). Barnes (1979) reviewed a number of other studies which have shown an negative curvilinear relationship between the productivity of herbaceous understorey and the density of trees or shrubs.

Conversely, in savanna composed of Brachystegia spiciformis Benth. and Julbernardia globiflora (Benth.) Troupin in Zimbabwe, Kennard et al. (1973) found that the end of season herbaceous biomass on sites with open canopies was 48% greater than in open grassland (the ratio of the average light intensity incident on the pasture was 1: 1.5: 4.1 in closed canopy, open canopy and open grassland sites). Aucamp et al. (1983) found in the E. Cape that maximum herbaceous production was found with densities of Acacia karroo equivalent to c. 300 trees/ha. Similar evidence has been provided by Sanford et al. (1983) for the Nigerian Guinea savanna, and they suggested that 25 to
50 large trees/ha would be an optimum density; they further noted that such densities also resulted in a composition of better quality herbaceous species.

Total herbaceous production on a site is of particular importance in farming systems where a seasonal surplus is harvested and stored for the season of shortage. However in many farming systems livestock rely only or substantially on grazing for their fodder. In such situations the important determinant of secondary production from the herbaceous component is not so much the total annual production but rather its seasonal availability and quality, and how these vary with annual fluctuations in climate.

Again the results from different sites differ considerably. Goldson (1973) found, on the Kenya coast, that the onset of pasture growth occurred earlier in the understorey of cashew trees compared to open sites and continued for up to 3 months longer during the dry season. Walker (1979) also referred to grass remaining greener for longer in the understorey of trees in some savanna types of South Eastern Africa, although in 1974 he referred (Walker 1974) to trials which showed that "cleared areas have a smaller inter-seasonal variation in grass production". Whilst Kelly (1977) has reported that improved understorey growth in South Eastern Africa was even more marked in drier, low-veld areas, other authors (eg. Barnes 1982, Ward et al. 1964, Walker 1974) have suggested that the influence of tree clearing on improved herbaceous production is particularly marked in dry years. Denny (1983) found with long term trials in Zimbabwe that the relative difference between cleared sites and sites with trees during wet years and dry years was determined by differences in soils;
on one site the difference in grass yields was similar between dry and wet years, while on another, during dry years the yields were 72% lower than on the cleared site and during wet years only 38% lower.

The significance of these varied results in understorey response must be assessed in terms of secondary production. In cases of higher pasture yields associated with trees which produce palatable foliage, secondary production would be expected to be considerably higher than on tree-less sites, particularly if a greater efficiency of utilization of the palatable biomass can be obtained by a mixture of browsers and grazers (eg. Aucamp et al., 1983, with goats and cattle on Acacia Karroo thornveld). In other cases, secondary production would be lower. Livestock responses to clearing "undesirable" trees have not always resulted in the expected response. Barnes (1979) referred to a study where the reduction Acacia hockii by up to 2400 bushes/ha had not resulted in an increase in cattle production. The extent to which the magnitude of the difference in fodder availability between tree-less sites and sites with trees is influenced by inter-seasonal and annual fluctuations in climate must be particularly important. Little concrete information appears to be available on this point, although the implications are that in some situations the availability of fodder would be reduced particularly at times where there is already a shortage of fodder. In other situations it is particularly during such periods of fodder shortage that the forage availability is improved by the presence of trees (eg. Larix decidua during dry years on south facing slopes in Valais, Switzerland, Kuonen 1980).
10.3.2. Pasture and tree production.

The influence of the herbaceous component on tree growth is equally variable both qualitatively and in magnitude, and may vary also with the size of the trees. Generally, weeding around a small tree improves the growth, even in situations where the herbaceous component is beneficial to the rate of tree growth once the trees have reached a bigger size (e.g., Pinus radiata with Trifolium subterraneum in Western Australia, Chevis 1984).

10.3.3. Integrated production.

The conditions of any one site (including all its temporal and spatial variability) must be a major determinant of the extent to which resources can be partitioned in a more efficient way in terms of primary production which is useful to secondary production or to man (e.g., fuelwood); for instance the presence of a water table in large areas of W Rajasthan make it possible for some tree species to rely on moisture which would not be available anyway to understorey plants. The ability to extend the nutrient tapping ability to larger volumes of soil in some mixed tree-pasture systems is also important. In terms of physical production, some systems combining trees with pasture result in higher overall production than would be achieved with either component alone. For instance the results of spacing trials with Pinus radiata in Western Australia have shown no difference in total cumulative yield between a treatment with closely spaced trees and one which would allow a considerable herbaceous production (McKinnell 1979).

For any particular site there must also be an optimum mix of trees
and understorey in terms of species composition which results in the best overall production from a mixed system at any one time, even if it is lower than would be achieved by the production of a single component. Some of the examples of positive and negative effects of trees on herbaceous production quoted above may have been altered by different species mixes.

Conversely maximum possible biological production on any site may be achieved by the use of monocultures of herbaceous or ligneous crops alternative to the ones which perform best in a mixture.

In newly established production systems (eg. plantations), the relative merits of mixed tree-pasture systems also depend on the relative value of the trade offs between alternative components during the rotation or production cycles of the system. For instance low value or costly thinnings can be replaced by valuable livestock products during the early years of the rotation (eg. McKinnel 1979 and Tustin et al. 1979 for Pinus radiata in Western Australia and New Zealand respectively).

The ability to maintain the balance between the various components of mixed systems, where this is desirable, requires a good understanding of the ways in which the various components interact and the flexibility in management to cope with, and where necessary compensate for variations in these interactions over-time. The management interventions which can play an important role in determining the nature of the interactions and which can also determine the composition of the production mix include for instance manipulation of the tree population (eg. thinning) or the individual tree (eg. stem pruning or lopping to reduce light competition); the use of fire to
influence pasture composition and quality (and hence palatability and nutritive value) and tree/shrub species composition, densities and age structure; the use of different proportions of livestock types which may promote the competitive ability of different components of the mix (eg. browser/grazer ratios). The timing of these management interventions can be crucial to the production of the system. The problem of mesquite in the semi-arid rangelands in the S.W. United States is a good example where it seems to be in large part the difference in management of the silvopastoral system which makes the difference between Prosopis spp. being perceived as a weed or an asset. Eradication in order to increase pasture and livestock production is suggested by most authors (eg. Martin 1975) and in Texas alone 1.2 M ha are treated annually with herbicides and mechanical equipment to "keep the encroachment of mesquite under control" (Fisher 1979). However some farmers claim that by appropriate grazing control and stocking densities a certain population and size distribution of mesquite can be obtained which actually improves livestock and game production (Maltsberger 1983).

10.4. Ownership, management and risk.

The evidence concerning silvopastoral combinations operational within farming systems indicates that the majority are within the confines of private ownership. This is on the understanding that the term "silvopastoral system" implies that there are clear objectives concerning its various components and that there is a deliberate management of these components aimed at satisfying these objectives (see Chapter 1 and section 10.6). The size of holding on which such
systems can be found and where the various components are under one ownership varies tremendously. Small mixed farms in the Kikuyu highlands of Kenya often have scattered trees of **Cupressus lusitanica** or **Croton** spp. on plots of grassland which may be less than 0.5 ha out of a total holding size of 1 ha (pers. obs.). Dairy farms in the sub-montane Canton of Coronado in Costa Rica which have an average size of 32 ha combine on the same site the production of **Alnus acuminata** for fuelwood and timber with well managed pasture. The stand densities vary from 35 to 625 trees/ha with 100 trees/ha giving a good compromise between both pasture and tree production objectives and an apparently increased net financial return of at least 20% over single product management units (Combe 1983). Very large silvopastoral enterprises exist for instance in New Zealand, Australia and the USA.

There are some systems which have successfully combined the production component from different ownership to the mutual benefit of both owners (eg. Government forest land and farmers' livestock, eg. Knowles *et al.* 1980 in New Zealand, Whyte 1957 in India). Some have even developed on communal grazing lands where the objectives of the community are effectively the cumulative objectives of its households or where strong community leadership or cohesion can control the objectives of individual households for the common good. In various communes of the Valais (Switzerland) **Larix decidua** has been able to get established in community summer grazing lands to the benefit of pasture production during dry years. Burrow (1983) has found that the re-establishment and strengthening of the power of elders in some communities of the East Pokot pastoralists in central Kenya has enabled strict grazing controls to be reinstated particularly over the
utilization of dry season grazing grounds; measures to thin undesirable
tree and shrub species and promote desirable fodder trees have also
recently been undertaken over several thousand hectares.

Silvopastoral systems exist in a wide range of forms with regard
to the complexity of management required. Some are fairly simple due to
relatively predictable climatic conditions and/or the resilience of the
components of the system in relation to fluctuations in conditions and
to each other; less intensive systems usually fall in this category.
The functioning of other silvopastoral systems is dependent on a high
degree of management expertise which has to rely on a good
understanding of the various ways in which the components of the system
interact. To derive maximum sustainable benefits from the semi-arid
savanna zones of Africa requires a combination of highly precise
combinations of management interventions (in terms of timing and
nature) which may include variations in stocking density, browser to
grazer ratios, the use of fire, manipulation of tree canopies and of
tree communities. Further because of the high seasonal and annual
variability in the climate, and therefore of the fluctuating nature of
interactions between components, it is easy to understand why there is
so much disagreement concerning the appropriate management of some of
these systems and even concerning their relative merits: eg. mesquite
rangelands in the S.W. USA, see above; the management of silvopastoral
systems in the savannas of south eastern Africa (eg. Barnes 1979, 1982,

The ability to develop effective silvopastoral combinations
depends on a number of factors. The initial stages in establishment of
the combinations may require a considerable amount of flexibility in
the management of a number of resources including cash, access to credit, labour and the degree to which the system which is already operating can be manipulated to incorporate new components (e.g., reduced grazing access for a few years, change in herd composition). There are a number of situations where silvopastoral development has been advocated to improve production, but because of a lack of flexibility their development is unlikely to be feasible (e.g., developing silvopastoral systems on W Rajasthan CPRLs). The degree to which small holdings are at an advantage or disadvantage over larger holdings in terms of flexibility, depends largely on the component of the farming system which needs to be flexible (e.g., labour or cash) and on differences in relative flexibility. The nature of the benefits will also determine the degree of attraction which such systems may have for farmers of different socio-economic status. Theoretically a pastoral system with a tree production component may give better results over single production systems when one discounts the likely returns from the tree component back to the present. However different people have different time preference rates, usually smaller farmers being less able to forego short term production for longer term increases in benefits. On the other hand a small farmer may price his labour at a lower rate than a larger farmer, thereby making it more attractive for him to introduce a few trees each year and to protect them. The degree to which government can influence the relative attraction of silvopastoral systems can be considerable (e.g., through cash loans or grants and in kind). Where the systems have potential on land which provides resources for different sectors of the community, the problem is to determine the compatibility of the interests concerned. This in
turn depends upon the extent to which politicians and administrators are committed to shifting the balance of interests where this is desirable. For instance, in Nepal and W Rajasthan, the relative contribution of common (or Panchayat) land is often considerably greater to the poorer than to the richer sectors of the communities. The latter may be keen to see such land afforested to timber species in order to provide revenue for community funds from which they often benefit most. The poorer households would often prefer to see a greater emphasis placed on fodder trees and pasture improvement which would contribute relatively more to their livelihoods. Where there are such conflicting interests, the introduction of silvopastoral systems, their management and subsequent success become increasingly difficult.

It has been argued that agroforestry helps to avoid conflicts and to harmonize diversification efforts in land use (Anon 1982). The extent to which conflicts may be resolved depends entirely on the objectives which different sections of society have for a piece of land and on the extent to which they are able to adopt and enforce compromises.

It has also been argued that agroforestry helps to diminish risk for individual farmers (and presumably for a community where the system is managed at that level of organization (Oldeman 1982, von Maydell 1982), and results in sustainable land management systems (King et al. 1978). These statements may be true in some circumstances and silvopastoral and agro-silvopastoral systems should incorporate these as objectives, but there are a number of situations where risk is likely to be increased and sustainability impaired by the adoption of silvopastoral systems. Risks can be increased for a number of reasons, those concerning the influence of trees on pasture production.
variability have been mentioned in section 10.3.1. The development of a silvopastoral system may be associated with the development of production components which — although of over-all higher production under expected circumstances — may result in greater susceptibility to natural phenomena or to the fluctuations of market prices. An investment of part of the production system in timber may result in increased risk if there is an unknown chance that trees will blow down. On the other hand if there is choice regarding the timing of timber sales, there may be reduced risk from an investment in two separate commodities. The repercussions of increased risk may be particularly significant if production components have been integrated (e.g. sheep breed changed to a more productive breed because of the introduction of shelterbelts) because this results in a greater system vulnerability; if one of the components suffers damage or loss (e.g. shelterbelt damage by wind). If the components of silvopastoral production systems are aimed at the market economy rather than subsistence and components are tightly integrated in order to maximize financial returns the whole system becomes vulnerable to fluctuating prices in the open market. For instance falling timber prices may reduce the financial attraction of thinning at a time when it is crucial to do so for the well being of the livestock component.

10.5. Research.

The purpose of applied research in the context of agroforestry should be to provide a range of alternative solutions which improve production and profitability on a sustainable basis. Research therefore needs to identify the constraints to production in farming
systems and to identify the potential benefits which agroforestry systems may possess. Research should also help to identify those conditions where integrated systems have the greatest chance of success. It appears from the W Rajasthan case study that considerable resources have been wasted because much of the silvopastoral research has been aimed at searching for inappropriate technical solutions to problems. The technical nature of these solutions makes their implementation unrealistic.

In most situations both time and resources are very limited. Therefore, once a potential role for the integration of tree-pasture-animal complexes has been identified, research should concentrate on identifying the desirable characteristics of the components which would make up the integrated system and on screening information available concerning candidate species, combinations and management regimes to be tested. This necessitates the critical interpretation of data available from elsewhere to assess whether the conditions under which the combinations are to be tried are sufficiently similar. However, even with an understanding of the interactions which resulted in the observed responses and production levels there are dangers in extrapolating from the results of one situation to possible consequences on other sites since there are often considerable difficulties in attributing observed responses to any particular factor or combination of factors.

Nevertheless, a number of lessons can be drawn for those who actually undertake and describe research on agroforestry systems. The investigations which have been discussed in this thesis show that a detailed description of site characteristics, including their variation
in time and space must be given with any description of interactions between the various components of the systems. Details regarding methodology followed, previous management history and current management of the components must also be given. There is a need for a systems approach to understanding interactions between the various components of agroforestry systems.

The application of multivariate analysis may help identify the key parameters which determine the nature of interactions and responses in tree-pasture-animal systems, however the value of multivariate analysis relies on having detailed and accurate data concerning parameters which do influence interactions and responses. Further, appropriate and detailed measurements need to be made of the responses of the organisms concerned (nature and timing of measurements and observations). From the range of interactions which have been found to be important in Chapter 2 to 5 it is likely that many research institutions, particularly in developing countries, are unlikely to have the resources to make sufficiently detailed measurements. The use of traditional experimental techniques using various treatment combinations and controls are essential to gain understanding of basic mechanisms resulting in observed responses under field and farm situations. However it must be realized that with the complex nature of the systems under consideration, changes in one factor usually result in changes in other factors which themselves have a bearing on responses. Experimentation under controlled conditions helps to identify treatment combinations (eg. row orientation, spacing, lopping cycle and intensity) which are likely to yield optimum production on a particular site type. It can also be used to screen appropriate
species and germplasm for desirable traits (eg. shade tolerance, water use efficiency, nitrogen fixation, resilience to lopping).

Farmers have an intimate knowledge of their environment, of its variability and of the way in which various components interact. Much more of that knowledge should be inventoried to improve awareness of potentially useful species, component combinations, management techniques and the subtle ways in which components interact under specific site and management conditions resulting in the variety of responses observed in different situations. Detailed monitoring of developments on farm units which take up new agroforestry technologies is likely to highlight problems and potential which research and extension services can use to improve those technologies. However, this requires planning and longterm commitments by researchers, extension workers, politicians, and administrators at all levels.

10.6. Sustainability and socio-economic development.

Agroforestry, including silvopastoral and agro-silvopastoral systems, is claimed to have considerable value in helping to improve the productive potential of sustainable land management systems (King et al. 1978). In so doing it is often said to have significant potential for contributing to economic development, particularly in fragile ecosystems (eg. King 1977, Mann et al. 1982). King et al. (1978) further stated that agroforestry implies management practices that are compatible with the cultural practices of the local population. Such land management systems would seem to be particularly attractive.

There is considerable theoretical evidence that tree-pasture-animal complexes can, given the right conditions (site, species,
management), result in a higher level of production on a more sustainable basis than can single component production systems. There are a number of farming systems where such integrated management production has developed. However the conditions under which these systems have developed indicate that a key condition of success is the ability to control the nature and magnitude of interactions of the various components of the system. This often requires the farming systems to have some flexibility in the management of resources which have bearing on the integration of various production components. It also requires the ability to arrive at a concensus as to how to manage common resources and control their management.

There are, therefore, severe doubts that silvopastoral and agrosilvopastoral systems can develop in many of the areas where they are supposed to have considerable potential. Many of the marginal and fragile ecosystems have reached levels of marginality and degradation because of the inability of communities to manage their resources on a sustainable basis. If they can get established at all, in such areas it may result in increased benefits. However, socio-economic development (as defined in Chapter 1) will only result if the benefits are fairly distributed between various sectors of communities and if the reasons which have led to marginality are tackled in the long term (eg. human and livestock population growth rate, expansion of agricultural land on rangelands). In farming systems which derive inputs from commonly managed resources, if the development of agroforestry systems removes some of the constraints on the utilization of common lands (eg. improved dry season fodder supply), the long term production potential of the system may indirectly be further jeopardized. The W Rajasthan case study also suggests that the
development of agrosilvopastoral systems on private land in combination with privatization of land utilization in a non equitable way has probably worsened the plight of the poorer sectors of the communities.

A number of so-called silvopastoral or agro-silvopastoral production systems do not possess one of the key characteristics of such systems - i.e. that of the deliberate promotion of woody perennnials (Anon 1982). Whilst the livestock component may have come to rely increasingly on trees for dry season fodder, and hence the level of interaction between the two components may be seen to be closer in some situations than it may have done in the past, it is because of reduced flexibility in management and a reduction of grazing resources that this dependence has come about. There are signs that due to increased impact on the tree component, both because of increased livestock densities and in the proportion of browsers to grazers, the ability of the tree component to regenerate may be decreasing and with it the sustainability of the system. Thus it would appear that King et al's (1978) implication, that agroforestry systems are attractive because they are compatible with the cultural practices of the local population, is often likely to be unrealistic. It is often because of the cultural practices of the local population that the environment has become degraded and that silvopastoral systems are unlikely to get established. Indeed, fundamental changes in attitudes, priorities and practices are required in most communities throughout the world before production systems become sustainable and lead to socio-economic development. It is only within the context of such changes that agroforestry and silvopastoral systems can make their contribution to socio-economic development.
10.7. Conclusions

This thesis has highlighted a number of issues concerning tree-pasture-animal production systems and their potential role:

1. The high degree of complexity of the interaction between various components of the systems;
2. The variability in the nature and magnitude of these interactions over time and space and between organisms of different genetic make up;
3. The ability of management to qualitatively and quantitatively alter these interactions and therefore responses;
4. The considerable benefits which can be obtained in a number of ways from these integrated systems;
5. The difficulties faced in attempting to understand the functioning of these systems and in undertaking appropriate research to obtain results which can be used to evaluate the potential contribution which such systems can make to production in any particular farming systems;
6. The likelihood that their development on communal land will only be successful where there is a considerable degree of institutional discipline;
7. The subject currently has considerable appeal and is attracting considerable funding, however there remain fundamental problems to develop appropriate research methodology to provide solutions for optimum management of integrated systems. Finally, the social and management situations under which the systems can be successfully implemented are highly specific and each situation must be considered on its own merits and there is little possibility of widespread generalization of solutions.