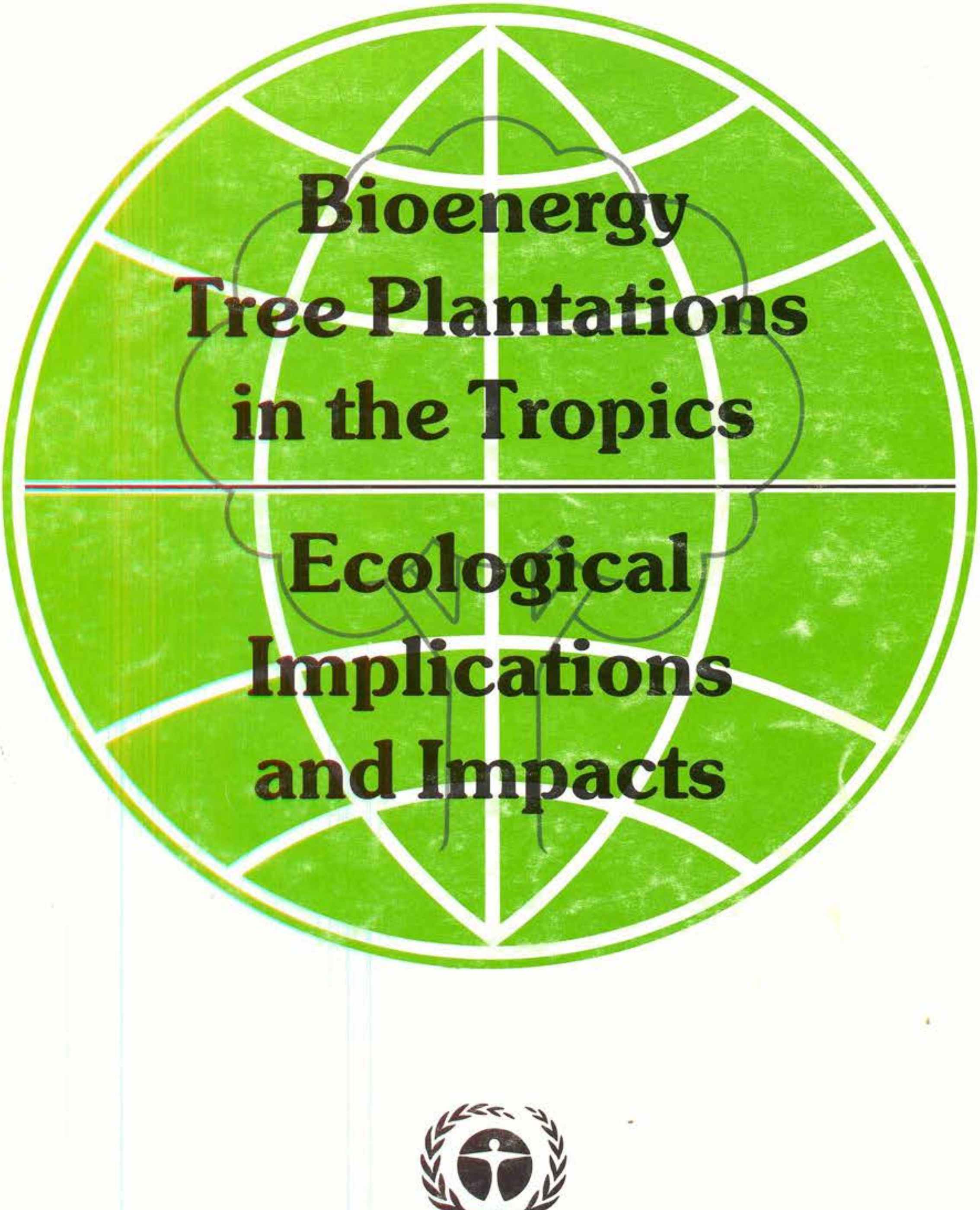

Bioenergy Tree Plantations in the Tropics

Ecological Implications and Impacts

Commission on Ecology Papers Number 12

International Union for Conservation of Nature
and Natural Resources

1987

IUCN Commission on Ecology

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- the relation between cultural values, socio-economic constraints and environmental management practices;
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Contents

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ABSTRACT

Present and future fuelwood deficits in the tropics and subtropics are reviewed. A case is made that bioenergy plantations have the potential to dramatically lower these projected shortfalls and, at the same time, reduce the pressure now being placed on the world's remaining tropical moist forests by fuelwood harvesting. Environmental and ecological considerations in raising bioenergy plantations are discussed. Yields and economics are set against social and institutional constraints to success. Agroforestry and increased use of wood waste are put forward as alternative and supplementary methods of increasing the supply of woodfuel. In the face of increasing population and progressive degradation of tropical forest lands, the creation of buffer zones around reserves and maintenance of ecological diversity outside the natural forest in terms of a diverse mosaic of heterogenous and discrete ecosystems are advocated. These strategies would include bioenergy plantations as a component. It is suggested that supplementing self-generating forest communities with planted ones is in no sense necessarily ecologically retrograde, provided the man-made plantings are set in context by a landuse plan which provides for adequate reserves of natural forests for nature conservation and landscape protection. A relatively stable ecological situation could be created in the landscape overall by directing the satisfaction of the energy demand in this way.

SUMMARY

Fuelwood production in the year 2000 may be only about 1.5 billion m^3 which is 1.1 billion m^3 short of estimated minimum requirements (up from the present 0.4 billion m^3 shortfall). As a consequence of the rapidly increasing world population and accelerating shrinkage of the resource base, as many as 3 billion people could face acute fuelwood shortages by the end of this century.

Several countries in the tropics, at the same time as they are experiencing difficulties in the supply of fuelwood for domestic use, are actively promoting the introduction and expansion of industrial activities based on woodfuel, such as tea drying, tobacco curing, brick, pottery and tile baking and lime and steel manufacture. Some expect also to produce electricity in rural areas using steam from wood-fired boilers. All these additional, non-domestic activities will mean fuelwood supplies will be streched even more thinly in the future.

While present wood energy deficits are reported mainly from the dry tropics and subtropics north and south of, but adjacent to, the tropical moist forest zone, the same or greater consumption pressures are now bearing down on the world's remaining tropical moist forest resources. The difference is that the deficits will not show up there until the forests are nearly all gone.

Bioenergy plantations, if properly sited and managed, have the potential quickly to reduce pressure on the world's remaining tropical moist forests, since they can take advantage of the very favourable growing conditions in many areas of the tropics and subtropics. The most important ecological aspects are correctly choosing species and properly matching those species to sites. Species selection involves many factors, including capacity for rapid growth on a wide range of sites, ability to produce wood of high specific gravity and high calorific value at a high solar energy conversion efficiency. Matching species to sites involves consideration of soil moisture requirements, soil pH, soil nutrient content, tree nutrition and species susceptibility to agents such as fire, soil salinity, diseases, pests and browsing by animals.

Present technology and silviculture are already adequate to establish ecologically sound, high-yielding bioenergy plantations. Social and institutional constraints, such as land tenure problems and inadequate training of field managers, in many places are limiting the chances of success.

Bioenergy plantations have potential for use as buffers between centres of very high population and areas of intact forest that are set aside for nature conservation. In much of the tropics, tall forest already has been replaced by low, secondary forest and thicket, and, in some places, by much more degraded types. There seems to be good reason to suppose that the progressive replacement of such a landscape by bioenergy plantations, shelterbelts and hedgerows would reverse the present degenerative trend and produce a more viable and no less ecologically effective landscape. The suggestion that self-regenerating communities should be supplemented by man-made ones is in no sense necessarily ecologically retrograde, provided the latter are set in context by a landuse plan which reserves adequate areas of natural forests for nature conservation and landscape protection.

In degraded and more intensely used areas, where the demand for fuelwood is greatest, the development of bioenergy plantations, woodlots, shelterbelts and hedgerows composed of monocultures or mixtures of exotics can only result in ecological improvement of

such areas. Such improvement may lead to a later stage where local species could be reintroduced into the landscape. Techniques of agroforesty have a place and best use must be made of wood which normally is wasted following harvesting in adjacent forest.

Ecological diversity can be maintained in terms of a mosaic of heterogeneous and discrete ecosystems rather than the type of diversity occurring within the single natural forest ecosystem which was lost. Since the energy demand will not suddenly go away or diminish, it seems prudent as soon as possible to direct the satisfaction of this energy demand in such a way that a relatively stable ecological situation can be maintained or recreated in the tropical landscape. Bioenergy plantations have an important role to play in this strategy.

1. INTRODUCTION

The state of planet earth is affected by famine, poverty, population pressure, deforestation, desertification, species loss and genetic erosion, pollution, deep human division and escalating violence (Myers 1985). The future is bleak and uncertain (Calder and Amirsadeghi 1983).

Uneven economic growth and rapid population increases (IUCN/IPPF 1984) coupled with high costs of fossil fuels in recent times have brought much of the human race into the arena of the so-called "energy crisis". While for the commercial sectors of the industrialized nations this energy crisis translated into the "oil crisis" of the 1970's, it is often forgotten that there is another energy crisis for the world's poor people, more than two billion of whom rely mainly on fuelwood for their energy requirements (Eckholm 1975). This latter crisis will not go away with a drop in oil prices. It will be aggravated further by intensification of the factors mentioned in the first paragraph, as population trends begin to overwhelm natural resources of all kinds (IUCN/IPPF 1984).

Many less developed countries depend largely on traditional sources of energy, most of which is renewable, such as animal dung, crop residues, charcoal and firewood. In the poorer countries these sources supply 50–75 per cent of the total energy used, or even more in places such as Bangladesh, for example. Overall they may account for the equivalent of 8.5 million barrels of oil a day, or roughly 20–25 per cent of the energy consumed in the developing world including China (World Bank 1979, 1980a,b). Renewable energies seem destined to increase their share in the future (Deudney and Flavin 1983).

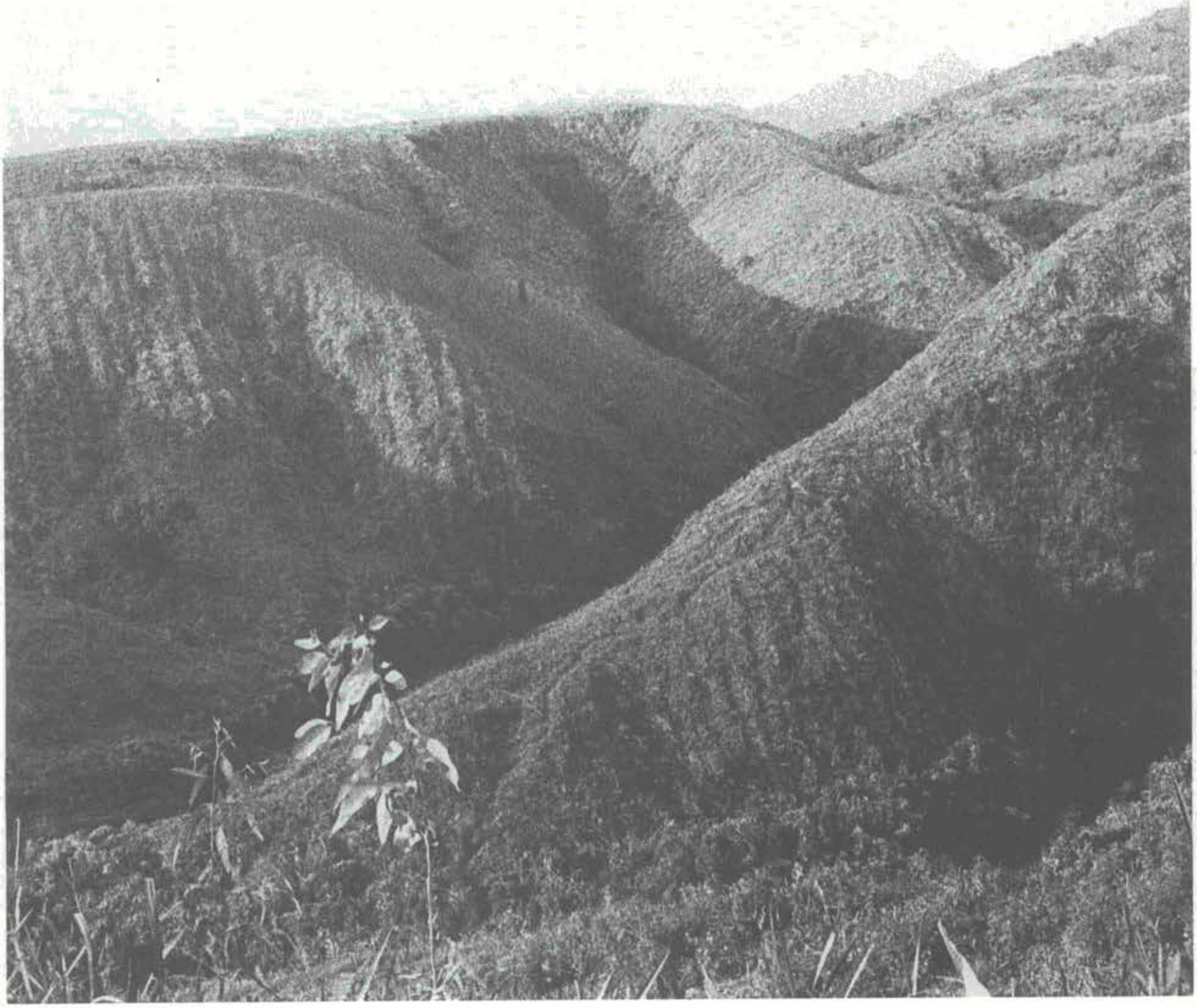
Future demand for wood of all kinds will exert ever increasing pressure on existing forests, particularly tropical moist forests and on trees grown outside those forests. The projected wood supply situation looks very different for the two main categories of consumption – industrial wood and fuelwood. Demand for industrial non-fuel wood, projected to the year 2000 (FAO 1982b), could be met on a sustainable basis from the world's remaining forests. Prospects for fuelwood, for both household and industrial use, by contrast, are nothing short of alarming. Fuelwood supply must be essentially local since normally its bulk and relatively low value do not permit economic long-distance transportation. By 1979 fuelwood consumption in developing countries (excluding China) had reached 1.3 billion m^3 but was already then 100 million m^3 short of requirements; an estimated 250 million people lived in areas of fuelwood shortage (FAO 1981a,b, 1983, Montalembert and Clement 1983). By 2000, potential demand, based on present per caput levels, is projected to rise to 2.4 billion m^3, but actual future needs to satisfy minimum requirements will probably be nearer 2.6 billion m^3 (FAO 1981a, 1982b, Montalembert and Clement 1983).

Because of the increasing population and shrinking of the resource base, fuelwood production in the year 2000 may be only about 1.5 billion m^3 which is 1.1 billion m^3 short of estimated minimum requirements (up from the present 0.4 billion m^3 shortfall). As a consequence as many as 3 billion people could face acute fuelwood shortages by the end of the century (FAO 1981a). This means that nearly all the people presently dependent on energy from fuelwood will experience difficulty in obtaining supplies, populations which have increased will experience the same or greater difficulty and new areas will experience deficiency. The result will be that poor people nearly everywhere in the tropics will not be able to cook their food regularly and adequately. Nevertheless, several countries in the tropics are also actively promoting the introduction or expansion of industrial activities based on wood fuel such as tea drying, tobacco curing, brick, pottery and tile baking and lime and steel manufacture. Many sawmills, pulpmills and other wood-using industries are supplementing their energy requirements with fuelwood to an increasing extent. Thus fuelwood supplies will be spread even more thinly.

Countries such as India and the Philippines have endeavoured to produce electricity in rural areas through generation using steam from boilers fuelled by wood, but in most situations these developments are constrained by the shortage of woody biomass, especially in heavily populated areas, where forest degradation has already gone far.

There is clearly a need to grow much more wood outside natural forests in both the dry and moist tropics. One way that this can be done is in intensively managed bioenergy plantations.

At an average yield of $10m^3$ ha/yr, which may be all that could be achieved under present practices, 100 million hectares of plantations, established at a rate of 10 million ha/yr, starting now, would be required. While this area at first might appear large,



An example of the many millions of hectares of tropical forest land altered by slash and burn agriculture and maintained in the altered state by repeated burning. This example, consisting largely of *Imperata* grassland, is from south-east Bangladesh. The area has just been planted with *Eucalyptus camaldulensis* at 10,000 trees/hectare to provide fuelwood for the nearby population on the plains which has a density of over 600 persons/km^2.

it was estimated by Lanly (1982) that the rate of deforestation in 76 tropical countries in the late 1970's was over 11 million ha/yr. Only one tenth of this was replaced with plantations of any kind.

If yield could be doubled to an average of 20 m^3 ha/yr, using improved breeding and cultural practices, the technology of which is available now (IUFRO 1982, Delwaulle 1983, Barnes and Gibson 1984), only about 5 million ha/yr of land would be required, but this still represents a five-fold increase in the present planting rate. Moreover, even if the massive financial input required (Spears 1983) to set up such bioenergy plantations is forthcoming, their establishment is unlikely to be entirely free of ecological and social problems.

Two types of utilization of bioenergy plantations are considered in this paper, one is the use of tree biomass as an industrial fuel, the other as fuelwood or charcoal.

The geographic area to be discussed has been limited to tropical and subtropical regions extending to a little north of the Tropic of Cancer and a few degrees south of the Tropic of Capricorn. In these regions (Fig. 1) are found together most of the developing world including the areas of most rapid population growth (Fig. 2a, 2b) and areas with critical shortfalls both of industrial energy and traditional fuelwood (Fig. 3). At the same time, because of favourable climates and higher than average levels of incoming solar energy (Fig. 4), many of these areas have high potential for production of bioenergy resources, particularly of woody biomass in fast-growing, frequently harvested crops.

Until a few decades ago the warm tropics were

A bioenergy plantation of *Eucalyptus camaldulensis* two years old in Bangladesh. This stand has been planted to provide fuelwood for drying tea. Paddy rice fields are located on flat land in the foreground. The ridge on which the trees are growing was unsuitable for intensive agricultural cropping, the soil being compacted, stony, very acid and formerly covered with *Imperata* grass. This plantation now also performs the function of a buffer between the heavily populated, fuelwood-deficient, agricultural lowlands and remaining patches of natural forest on the hills behind.

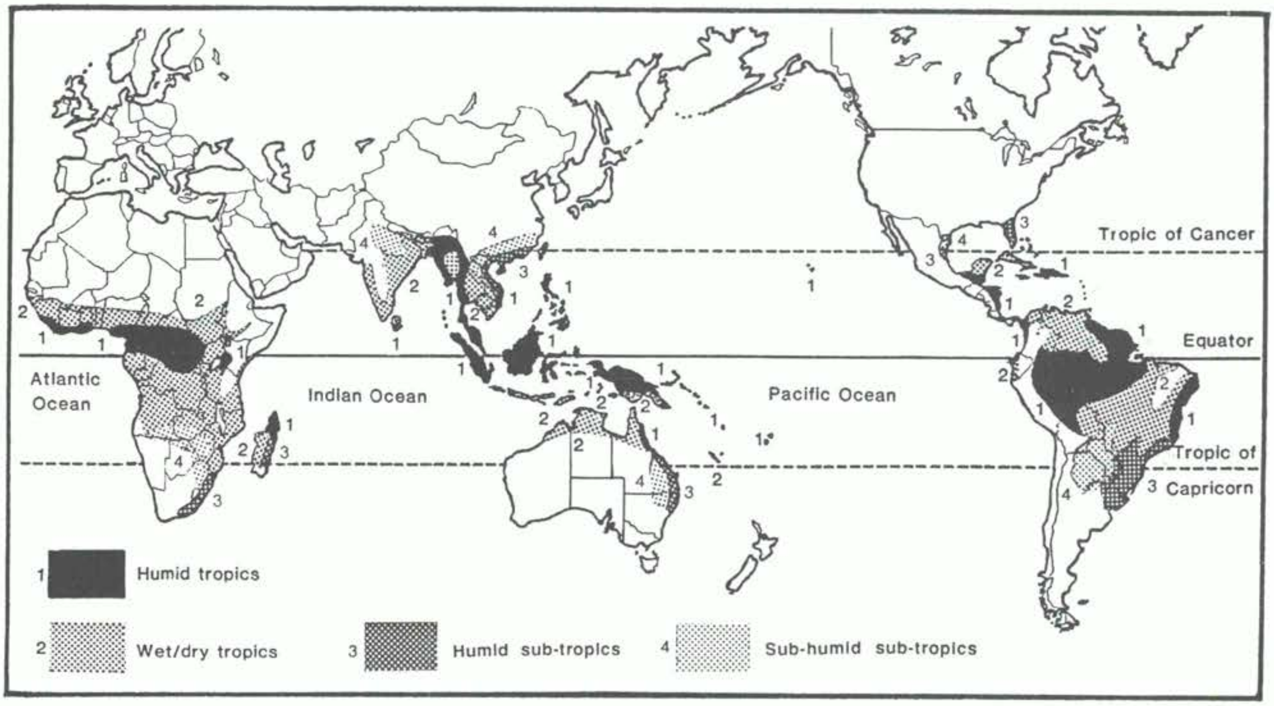


Fig. 1. The tropical and subtropical climatic regions of the world.

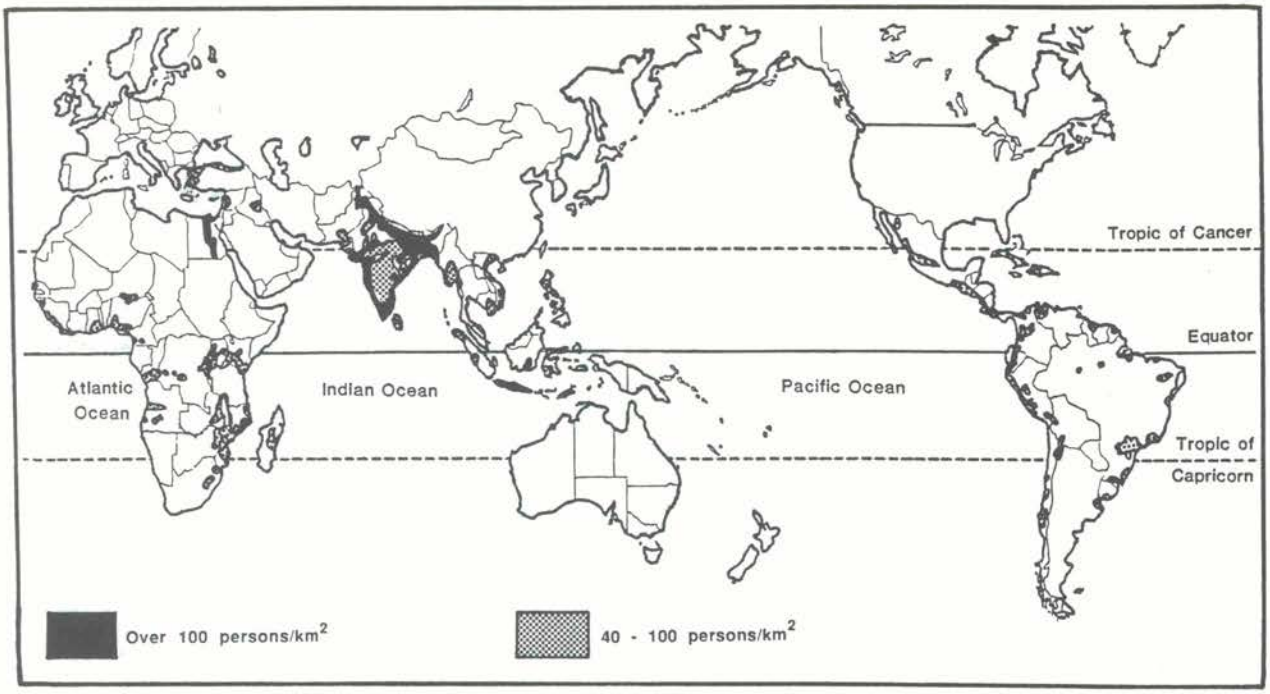


Fig. 2a. Areas in the tropics and subtropics with population densities of over 40 persons/km^2.

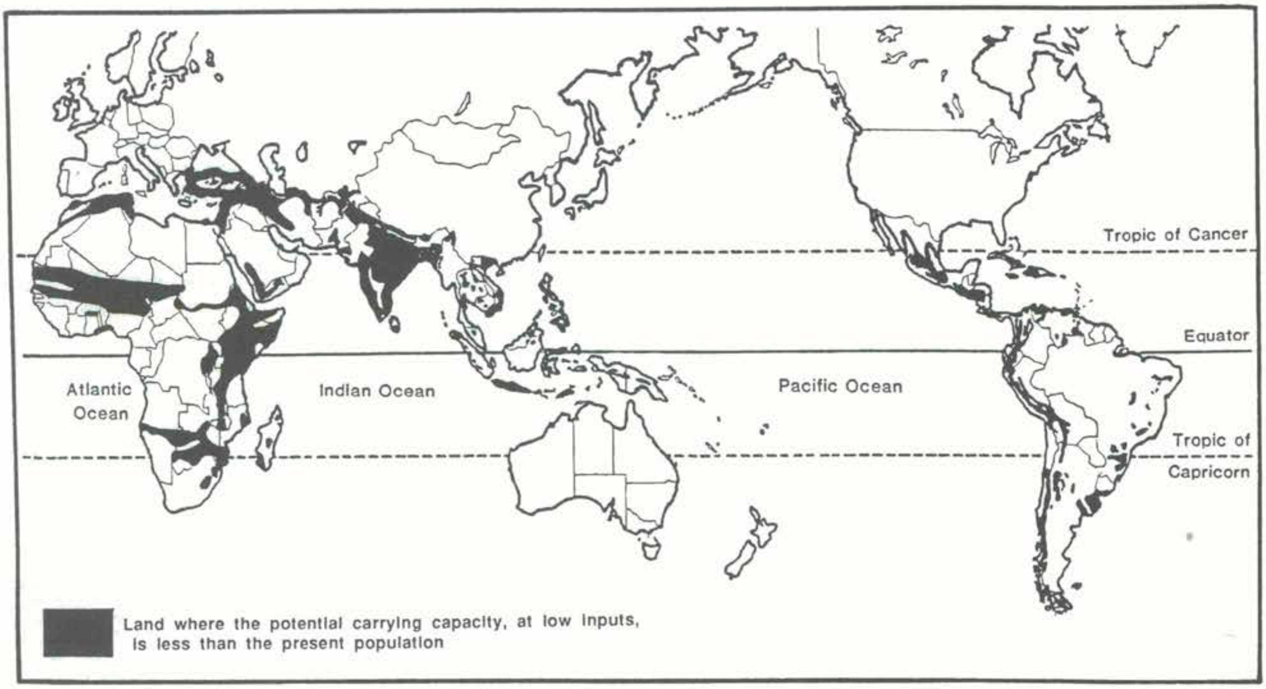


Fig. 2b. Areas which could not support their 1975 populations even if all the cultivated land within them was used to grow nothing but food crops. By "low inputs" is meant a level of farming used by most subsistence farmers in developing countries today. The total extent of these critical areas exceeds 24 million km^2. Already a decade ago the combined populations of the critical areas exceeded 1.1 billion of which about 544 million persons were in excess of the carrying capacity of the land (information from Harrison (1983)). The present situation is much worse.

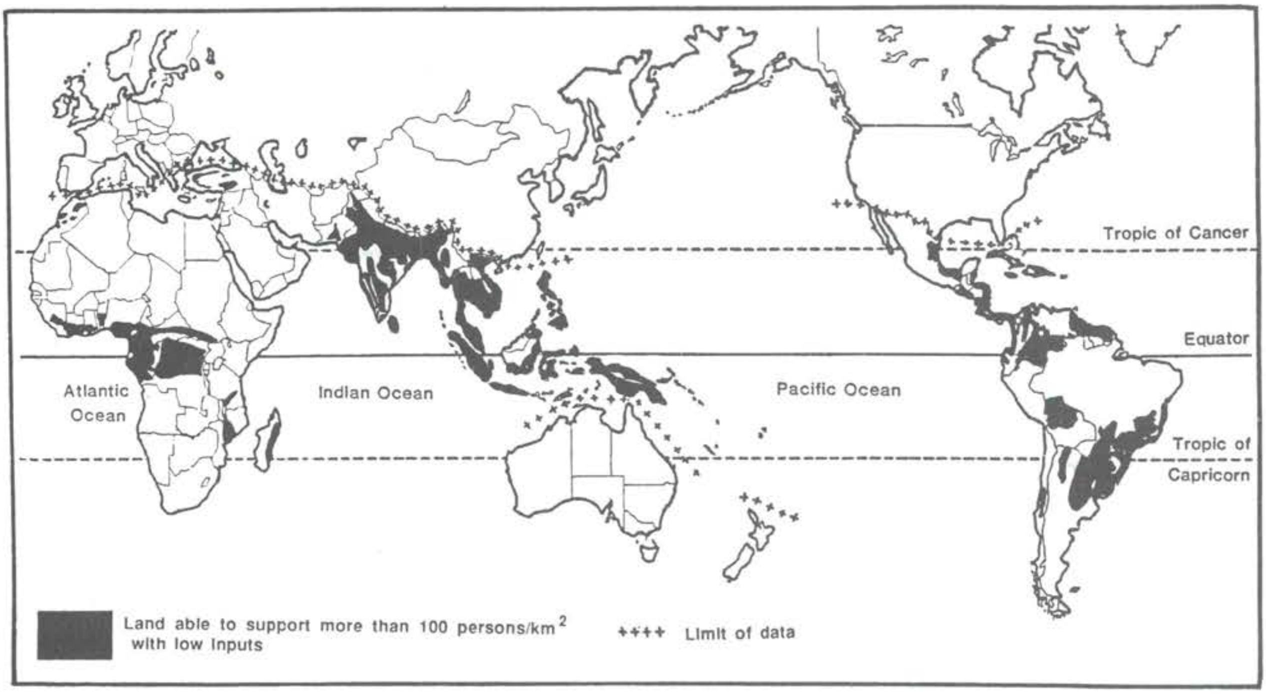


Fig. 2c. Areas able to support more than 100 persons/km^2 with low inputs. By "low inputs" is meant a level of farming used by most subsistence farmers in developing countries today (information from Harrison (1983)).

relatively sparsely settled compared with the cooler and drier zones adjacent to the north and south. This was because of many factors: the higher incidence of diseases of humans and their domestic animals in hot and humid conditions; dense tropical forests which required considerably more energy to clear than temperate ones; difficulties of working in the tropical heat; ecologically fragile soils and the rapid growth of weeds.

Recently, however, because of the better control of diseases such as malaria, cholera and typhoid and the fact that many parts of the tropics cannot support more people than there are in them at present (Fig. 2c), people are now being driven by the growth of population into the remaining tropical forest areas (Fig. 4) at an increasing rate, just as happened earlier in south Asia, for example in India and Bangladesh, and parts of southeast Asia such as Java, even before there were substantial advances in medical and agricultural technology. This means that the tropical moist forest is now experiencing a wave of planned and unplanned settlement causing the resource to be rapidly depleted by clearing for agriculture and, especially in the drier areas, by fuelwood collection.

While present well-publicized areas where there is a shortage of wood for energy purposes are found mainly in the dry tropics, such as the Sahel, the same or even greater pressures will bear down on the natural forests of the moist tropics, where deficits will not show up until most of the tropical moist forests are gone. The International Union of Conservation of Nature and Natural Resources (IUCN), in its concern for the conservation of the tropical moist forests, would like to see the pressure to use these forests for fuelwood reduced and diverted as soon as possible.

Bioenergy plantations if properly sited and managed (CAB 1982, Whitmore *et al*. 1986) have the potential to reduce pressure on the world's remaining tropical moist forests (Huguet 1983, Davidson 1985c, Davidson *et al*. 1985), but the pitfalls are many. IUCN is particularly concerned with any possible harmful effects of bioenergy plantations on the environment.

2. ENERGY ALTERNATIVES

Renewable energy resources, which now supply 18 per cent of world energy (Flavin 1985), can be classified into three broad categories:

i. biomass in its traditional solid forms (e.g., wood, charcoal and agricultural residues)
ii. biomass in non-traditional forms (e.g., converted into industrial charcoal, liquid and gaseous fuels) and
iii. solar, wind, small-scale hydropower, geothermal and tidal energy.

In considering the qualitative usefulness of these various sources of renewable energy it must be taken into account that some are relatively expensive (e.g.,

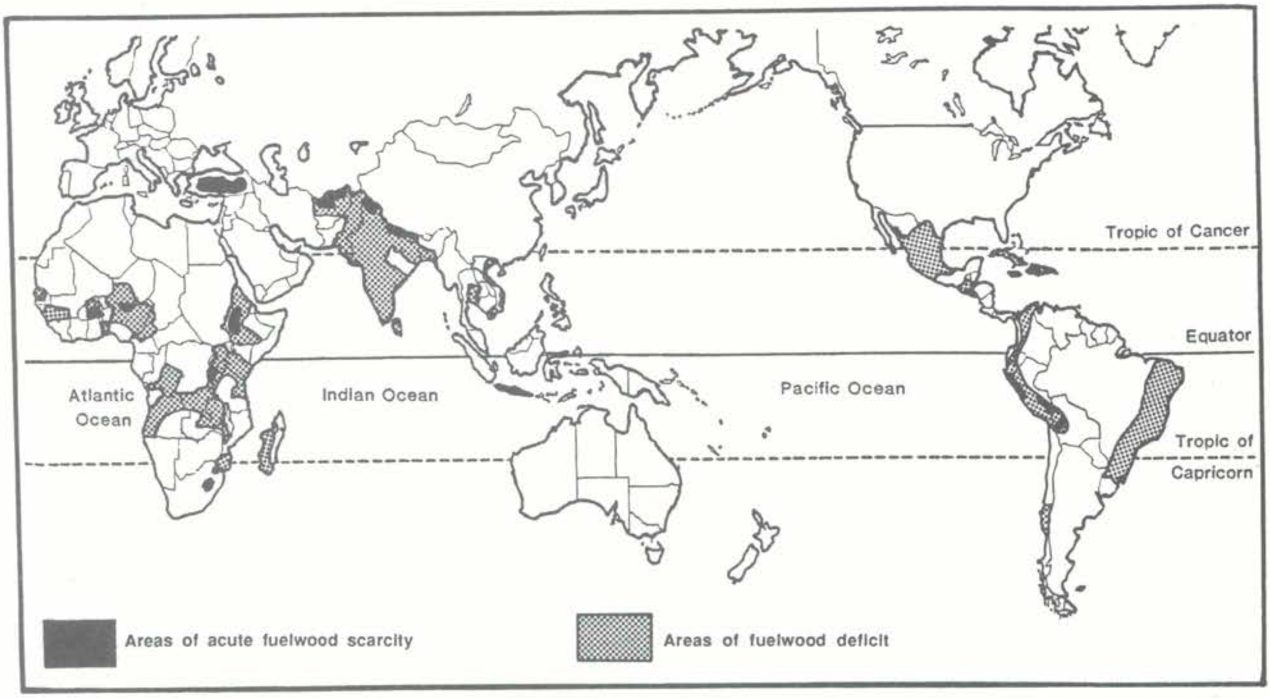


Fig. 3. Areas of fuelwood shortage. By "acute scarcity" is meant fuelwood resources have been so reduced that the population is no longer able to ensure a minimum supply. A "deficit" situation means present fuelwood resources are below requirements, obliging the population to over-exploit the resource. This information comes from FAO (1981b). The term "fuelwood" is used here to refer to wood in the rough form from trunks, branches and other parts of trees and woody shrubs used as fuel for such purposes as cooking, heating or power generation through direct combustion, not only in households and villages but also in rural industries and for conversion to other fuel products such as charcoal.

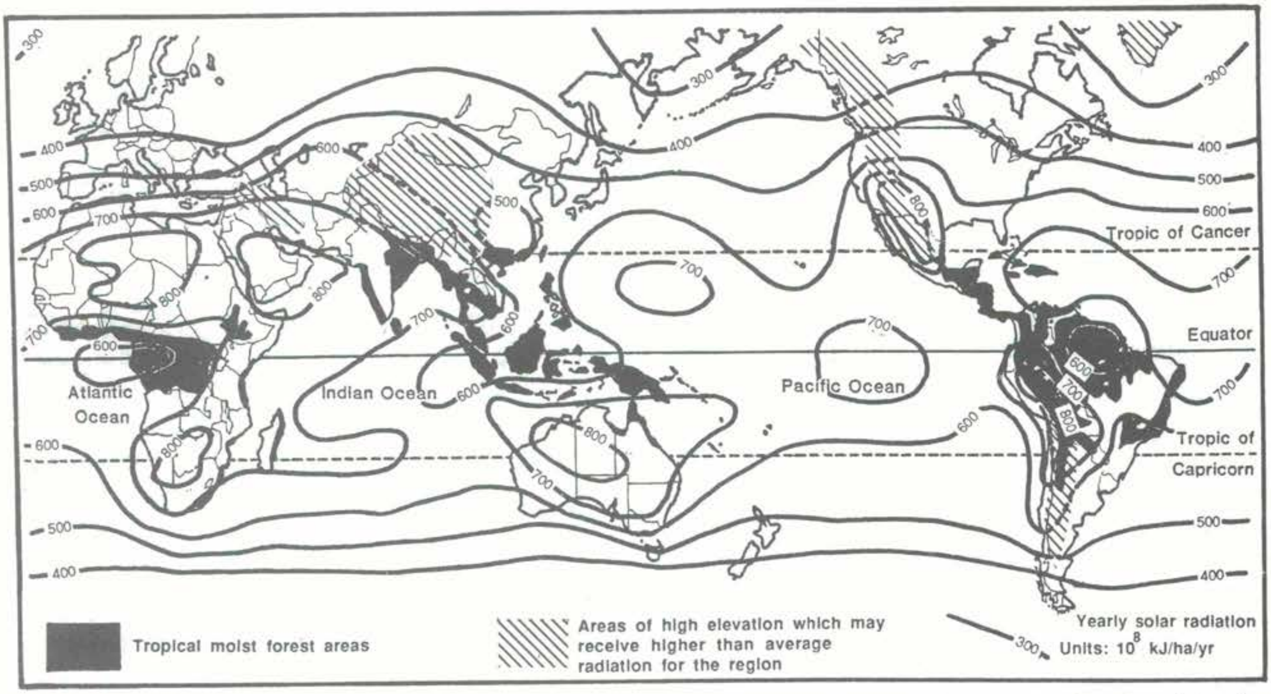


Fig. 4. Distribution pattern of yearly solar radiation levels at the surface of the earth. Also shown is the distribution of tropical moist forest areas (from Davidson (1985c)). The higher radiation levels received in the tropics are evident. The exceptions are in equatorial Africa, Indonesia and Amazonia where cloudiness reduces the average yearly radiation.

TABLE 1
Rural energy needs in developing countries which are or can be met by renewable energy sources

Need	Form of energy required at Point of Use	Biomass	Solar	Hydro	Wind	Geothermal
1. Cooking	Heat (100–300°)	S	L	–	–	–
2. Water heating	Heat	S	L	–	L	S
3. Space heating	Heat	S	L	–	L	S
4. Space cooling or heat (120–300°)	Mechanical/electrical	L	L	L	L	L
5. Water pumping						
(a) Domestic	Mechanical/electrical	L	L	S	S	–
(b) Animal needs	Mechanical/electrical	L	L	–	S	–
(c) Irrigation	Mechanical/electrical	L	L	S	S	–
6. Water purification	Heat or mechanical/electrical	S	S	L	L	S
7. Industry	Heat (160–150°) (Mechanical/electrical)	S	S	S	L	S
8. Lighting	Electrical/chemical	S	L	S	S	S
9. Communication	Electrical	L	S	S	S	S
10. Transport	Mechanical	L	–	–	–	–

Note: S: Good prospects for use in the short-to-medium term (0–10 years)
L: Good prospects for use in the medium-to-long term (over 10 years)
Source: OECD (1979).

involving photovoltaic and photochemical processes), some may be available only in certain localities (e.g. wind and tide energy), be extremely localized (e.g., geothermal energy) or unlikely to make any worthwhile contribution in the short term (e.g., ocean thermals).

During the 1970's the greatest emphasis in research was placed on solar technology (56%), followed by forest biomass and biogas (26%), wind (9%), geothermal (7%) and micro-hydro (3%) (OECD 1979). In developing countries, more emphasis has to be placed on woody biomass, because the dominant requirement is for cheap heat to cook food and boil water (Table 1) and solar technology is still too expensive for very poor rural communities. Even small-scale, simply-constructed biogas generators are too expensive for the poorest of the poor.

There is little argument, therefore, against bioenergy plantations being an appropriate means to produce the bulk of additional energy required by the developing world. The problems lie in how to implement this.

3. USING WOOD FOR ENERGY

Forest tree biomass can be used directly as wood fuel or it can be converted into many different other products, among which are solid (charcoal), liquid (ethanol, methanol, liquid hydrocarbons and oil) and gaseous (methane and synthetic gas) fuels (Egneus and Ellegard 1984).

Five principal methods of obtaining energy from wood will be discussed briefly; these are:

i. burning as a source of heat
ii. conversion to charcoal
iii. conversion to gas
iv. conversion to ethanol
v. electricity generation

3.1 Burning as a source of heat

The most common and most basic use of wood as a fuel is by burning, either using the heat directly for cooking and space heating or indirectly by burning in a boiler to produce steam. A measure of the fuel value of wood is its gross calorific value. This value, expressed as kJ/kg of oven-dry wood, varies with few exceptions by only about 5 per cent. For different species the total range is from 12,000 to 23,000 kJ/kg with a mean of about 19,500 (Conder 1973, Fung *et al*. 1978, Harker *et al*. 1982).

Fuel value for a given volume of wood depends more on the density of the piece than on the gross calorific value of the wood substance. The thick cell walls and high lignin and resin contents which contribute to high specific gravity of the wood of some species result in those species having a high value for fuel. Some resins and other volatile products in wood can produce unpleasant odours and smoke which can pollute food being cooked and contaminate living spaces in dwellings.

Moisture in wood greatly decreases its calorific value because burning damp wood consumes some energy to evaporate the moisture (Tisseverasinghe 1983). For a typical case, oven-dry wood with a moisture content near zero per cent has a gross calorific value of about 19,500 kJ/kg (Fig. 5). At 20 per cent moisture content ("air-dry" in parts of the tropics and subtropics) the same wood has a gross calorific value of under 19,000 kJ/kg while at 200 percent moisture content (typical of young, green wood of several fast-growing species consisting mainly of sapwood) the calorific value is only about 14,750 kJ/kg (Fig. 5) and may be as low as 10,000 kJ/kg when freshly cut (Table 2). Because of the low heat value of green and moist wood, the potential gain from improved wood drying could be significant for conservation of fuelwood and forest resources. Provision for fuelwood drying should be considered in any fuelwood programme, although storage may not always be practicable.

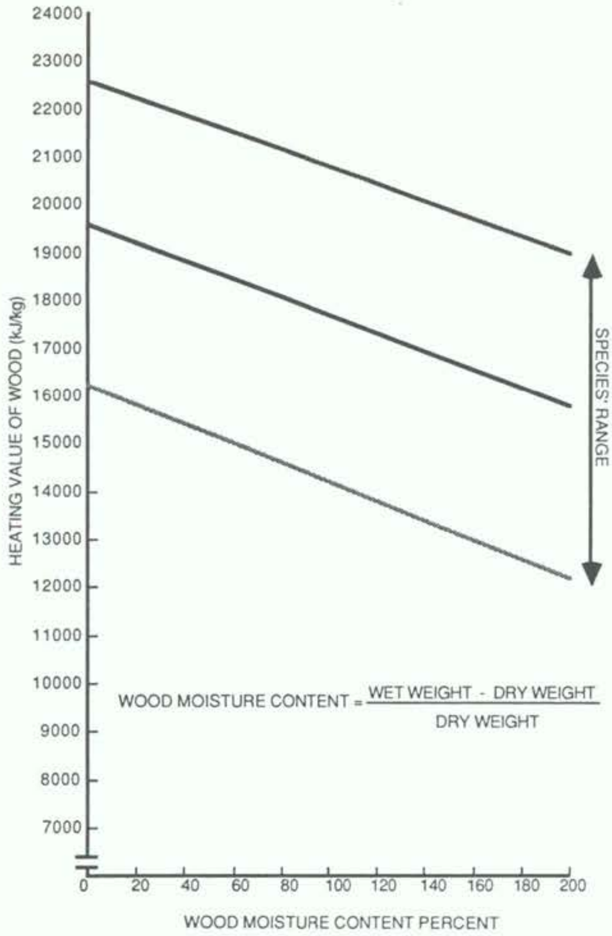


Fig. 5. Heating value of wood declines rapidly with increasing wood moisture content. Promoting a greater degree of fuelwood drying would lead to considerable conservation of wood resources.

3.2 Conversion to charcoal

Wood fuel has the disadvantage that dry wood has only about half the calorific value of oil (Table 2) and half its density. To obtain the same heating value, about four times the solid volume of wood has to be transported. More volume, typically one quarter to one third depending on diameter of billets and packing arrangement, is occupied if wood is transported as logs or billets. Less volume is occupied if the wood is first reduced to small chips.

Another way that wood can be decreased in volume and weight and at the same time upgraded in heating value is by conversion to charcoal (CAB 1979) which has a calorific value of 30–32,000 kJ/kg or about two-thirds the energy value of fuel oil (Fung 1982) (Table 2). About three tonnes of oven-dried wood produces about one tonne of charcoal (Table 2). Charcoal has an advantage over wood where smokeless combustion is required, since it is a clean-burning fuel. The production of charcoal by the pyrolysis of wood has been carried on for centuries. Methods employed now range from batch processes which include the simplest, primitive stack method, where a smouldering pile of dry wood is covered with earth and provided with draught holes

TABLE 2
Forms of wood energy

Use	Wood		Energy equivalence	Remarks
Source of Heat	Freshly Cut (Green)	1t	10 500 MJ = 1/4t Fuel oil*	
	Air Dry**	1t	18 200 MJ = 2/5t Fuel oil	
	Oven Dry	1t	20 000 MJ = 1/2t Fuel oil	
Charcoal Manufacture	Oven Dry	3t	Produce 1t charcoal = 31 000 MJ = 2/3t Fuel oil	
Ethanol Production	Air Dry	1t	Produce 160 litres ethanol = 3640 MJ	
Electricity Generation	Air Dry	1t	1 260 kWh or	Condensing Turbine 25 per cent efficiency
			510 kWh + 11 600 MJ	Back Pressure Turbine – Cogeneration

* Fuel oil calorific value = 44 700 MJTt
** 20% wood moisture content on an oven-dry basis.
Note: For several fast-grown tree species it takes up to about two tonnes of freshly cut green wood to yield one tonne of oven-dry wood.
Source: Altered from Fung, 1982.

and chimney, through types of charcoal kilns of various levels of sophistication which offer better control over rate and degree of combustion, to very complex, automated, continuous carbonization retorts (Fung 1979, CAB 1979). The batch-operated systems are more common, are generally labour intensive, and require a degree of skill for successful operation. Both product quality and uniformity are difficult to control. Nevertheless, they include designs which are simple and inexpensive to set up and are suitable for small entrepreneurs and cottage industries in developing countries (Fung, 1982).

Conversion to charcoal can adversely effect resource conservation because only about half the energy in the wood is recovered, the remainder being lost in the volatile smoke and gases which are allowed to escape in the simpler batch-operating systems. If the volatiles are burnt and the heat recovered, the energy of the original wood charge is more fully utilized, pollution is lessened, and there is reduced pressure on the forest resource.

Charcoal is a suitable solid fuel for industrial applications, such as manufacture of steel, as well as for domestic cooking and heating. Pulverized charcoal can be mixed with liquid fuels and fed into oil-burning furnaces (CAB 1979).

3.3 Gasification

Wood can be converted into a gas for burning in boilers or for running internal combustion engines. Gas producers fired on charcoal, and to a lesser extent on wood, were used on trucks and cars to supplement petrol and diesel fuels during World War II (Cash and Cash 1942, NAS 1980). Studies in the Philippines have shown that producer gas alone can be used to run a petrol engine while a diesel engine will run on a mixture of producer gas and diesel oil, thus reducing the consumption of diesel by 90 per cent. Biomass gasification in developing countries has been reviewed by Foley and Barnard (1983). Commercialization of gasifiers for vehicles and stationary engines is occurring on a significant scale in Brazil and the Philippines.

3.4 Ethanol production

Fuel ethanol can be produced from wood by hydrolysis into sugars followed by fermentation and distillation (Riehm 1960). About one-fifth of the energy in wood is recovered in the form of ethanol. One tonne of air-dry wood can produce about 160 litres of ethanol (Table 2). This can be used directly in specially modified engines or as a blend of up to one-quarter with petrol in existing engines following minor retuning. This type of fuel mix is mandatory in Brazil to reduce dependence on oil imports. Up till now ethanol has been derived almost entirely from sugar-cane and cassava, as in Papua New Guinea, for example.

3.5 Electricity generation

Electricity can be generated by burning wood in a high-pressure boiler producing superheated steam to run a turbine-powered generator. Generation efficiency is the ratio of electrical energy produced to the fuel energy input. For large thermal power stations an overall efficiency of about 30 per cent can be expected. For smaller generating units using wood, fuel efficiency is normally lower at around 25 per cent or even less. This means one tonne of air dried wood can produce about 1200 kW.h of electricity at best (Table 2). Small plants run intermittently may yield only half of that (Tisseverasinghe 1983).

Co-generation is the process whereby high pressure steam is produced to run a back-pressure turbine generator and the exhaust steam from the turbine is used also for heating purposes. In this way the overall thermal efficiency can be increased to about 75 per cent, but at the expense of a much reduced electrical output. One tonne of air-dry wood in co-generation will produce about 510 kW.h of electricity and 11,600 MJ of heat energy (5.1 tonnes of steam) (Table 2) (Fung 1982).

4. THE EFFICIENCY OF TREES AND PLANTATIONS IN CONVERTING SOLAR ENERGY

The efficiency of photosynthesis sets the ultimate limit on crop productivity (Beadle *et al*. 1985). The plant kingdom is the largest solar energy convertor on this planet. Net primary production each year through the process of photosynthesis is 3×10^{21} Joules – about 10 times the world's estimated annual use of all forms of energy (3×10^{20}J) (Hall 1984). The amount of energy in total standing biomass (90 per cent of which consists of trees) is about 20×10^{21}J or slightly less than the estimated energy in present fossil fuel reserves (25×10^{21}J) (Hall 1979, 1984).

The solar constant or the average total radiation energy received from the sun per unit of area on a theoretical surface perpendicular to the sun's rays and at the mean distance of the earth from the sun, corrected for atmospheric effects and seasonal changes, is about 440×10^{8}kJ/ha/yr. In the tropics and subtropics and at high altitudes more of the sun's incident radiation reaches the earth's surface than at high latitudes, provided cloud cover is low (Fig. 4). Photosynthetically active radiation is about 40 per cent of total radiation or about 175×10^{8}kJ/ha/yr.

Much of the photosynthetically active radiation is absorbed by plants but only a small quantity is fixed in plant woody tissues which may be subsequently released by burning biomass fuels. The ratio of the amount of photosynthetically active radiation that falls on the plant canopy to the amount of energy fixed by the plants is termed the energy conversion efficiency (ECE). Although the efficiency of utilization of solar energy at the cellular level is theoretically relatively high at around 30 per cent in terms of gross assimilation (Kok 1973, Kok *et al*. 1976), net assimilation is much less, because energy is lost in processes in the living plant such as respiration. The actual maximum ECE at the cellular level is probably near 12 per cent. Several comprehensive reviews are available describing the processes and pathways involved (e.g., Jackson and Volk 1970, Hatch 1971, Tolbert 1971, Zelitch 1971, Beadle *et al*. 1985).

Estimates of the ECE of forest systems are few. The maximum solar ECE by woody plants in general is probably between about 6.6 per cent (e.g., Gurumurti and Raturi 1981) and 11 per cent (e.g., Schneider 1973). Hall (1979) has calculated the global ECE in plant systems and concludes that trees make the greatest contribution to solar energy conversion in the world, even though the efficiency of trees is as low as 0.2 to 0.5 per cent on a global basis. Gurumurti (1981) has outlined the causes of low ECE in trees.

An ECE of 0.4 per cent was reported to be very good for temperate tree crops by White and Plaskett (1981), while Szego and Kemp (1973) were of the opinion that an ECE of at least 0.7 per cent could make temperate short rotation bioenergy plantations feasible and economical.

Frissel *et al*. (1978) described yields of *Populus* sp of 15 dry tonnes/ha/yr which suggests an ECE of about 1.8 per cent. Yields of *Casuarina equisetifolia* obtained by Seshadri *et al*. (1978) had a calculated ECE of over one per cent. Gurumurti *et al*. (1984a) reported a figure of 1.26 per cent for a three-year-old close-spaced *Eucalyptus* plantation. They also noted two peaks in seasonal solar ECE, one at 18–24 months and another at 30–36 months, reaching 1.77 and 3.26 per cent respectively of photosynthetically active radiation and the peaks corresponding to periods of additional moisture availability for growth (Gurumurti *et al*. 1984a,b).

For three-year-old close-spaced plantations of *Dalbergia sissoo*, *Cassia siamea*, *Acacia nilotica*, *Eucalyptus tereticornis* and *Albizia lebbek* grown in India, ECE's of 2.09, 1.58, 1.44, 1.26 and 1.19 per cent were calculated based on utilizable biomass yields of 28, 21, 23, 15 and 17 t/ha/yr respectively (Kimothi 1984, Kimothi *et al*. 1984).

Pilot plots of *Eucalyptus camaldulensis* and *E. tereticornis* planted at 0.9 × 0.9 m spacing (over 12,000 plants/ha) and grown for five years in Bangladesh have shown a solar energy conversion efficiency of 5.8 and 4.8 per cent based on above-ground biomass yields of 51 and 42 t/ha/yr respectively (Davidson and Das 1985). The yields reported are unlikely to be as great in routine plantations, because small research plots receive light from the side as well as from above. Realistic expectations would be about half these yields. These citations are included here mainly to show the range of ECE values reported. Without details being made available on the actual site quality and management regimes, ECE's are not directly comparable from species to species and place to place. Only by adopting some average calorific values and the range of productivity of biomass for each of several species is it possible to compare their relative average solar energy conversion efficiencies (Fig. 6).

Based on these data and the discussion above, it appears reasonable to state that prospects for commercial success are better if bioenergy plantations are established only with those species on those sites which will yield not less than one per cent and preferably over two per cent solar ECE (corresponding to about 10 and 20 t/ha/yr above-ground biomass production respectively) (Fig. 6) over rotations of about 5 years. These expectations are tempered by site quality (Fig. 6).

Among the better performing species are *Sesbania* spp. some *Eucalyptus* spp, *Casuarina* spp and *Leucaena leucocephala* (Fig. 6). The range of values shown can be put into perspective when compared with sugarcane which, even under very intensive cultivation practices, is observed rarely to exceed 3 per cent solar energy conversion efficiency (Mathur *et al*. 1984).

5. ENVIRONMENTAL AND ECOLOGICAL CONSIDERATIONS IN RAISING BIOENERGY PLANTATIONS

As with any crop system, successful tree husbandry depends on several factors among which are:

i. selecting the most appropriate species (e.g., see Turnbull and Pryor 1978; Webb *et al*. 1980)
ii. using seeds of good quality (e.g., see Faulkner 1975, Boland *et al*. 1980, Zobel and Talbert 1984)
iii. raising healthy seedlings for transplanting (e.g., see Evans 1982)
iv. correctly matching species to sites (e.g., see Davidson 1985a)
v. using proper planting practices (e.g., see Chapman and Allan 1978, Evans 1982)
vi. promoting adequate aftercare (weeding, protection from browsing) (e.g., see Evans 1982).

Most of these factors have environmental and ecological implications.

5.1 Species selection

Little (1983) described 90 species of fuelwood crops while various National Academy of Sciences (NAS)

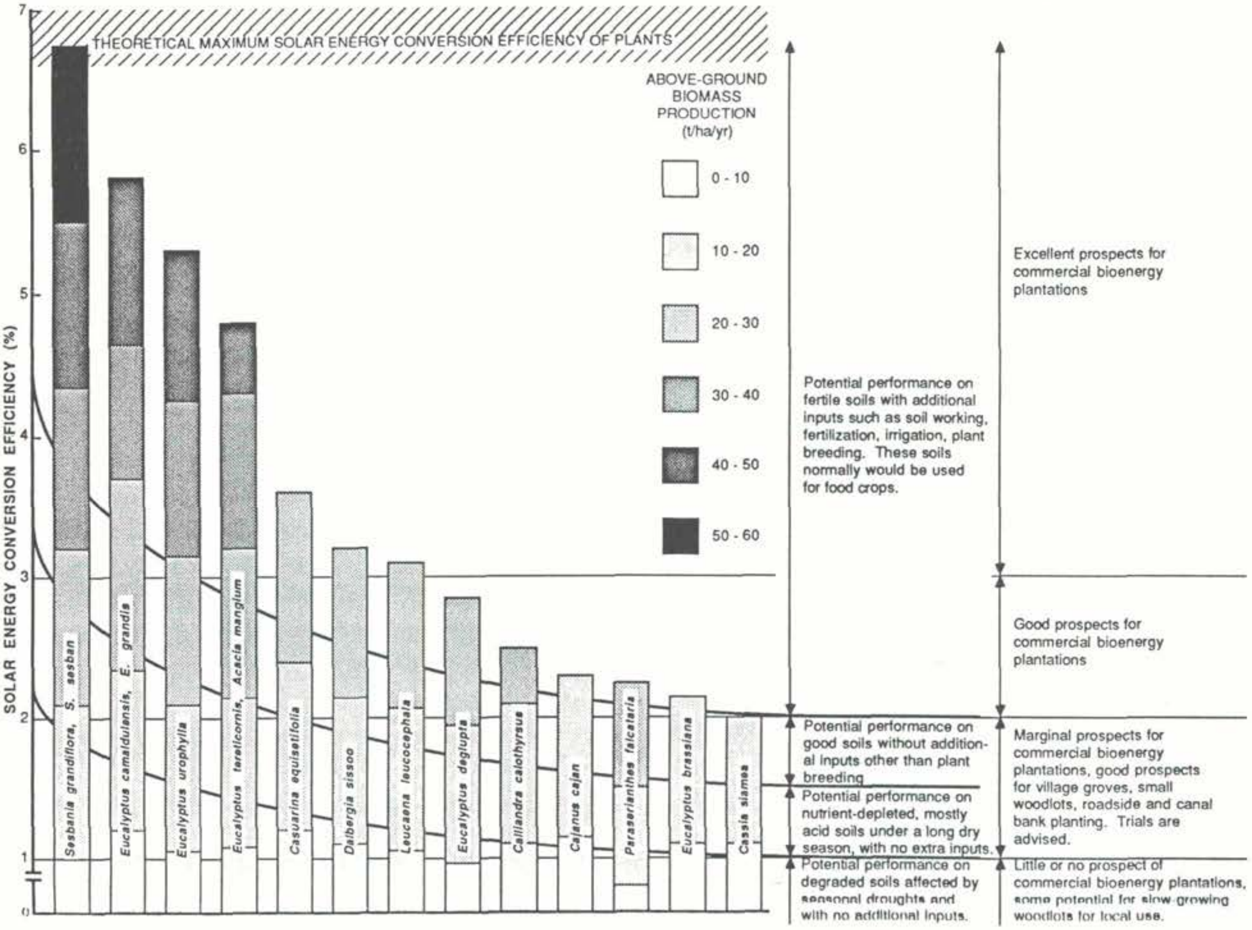


Fig. 6. The relationship between solar energy conversion efficiency (ECE) and above-ground biomass production in plantations of several different species. The range of species' performance is derived from the author's experience and a large body of literature. While solar ECEs of above two per cent may be necessary for profitable commercial bioenergy plantations at present, lower ECEs are adequate for trees grown for non-commercial use on farmers' land, in village woodlots and in other places where extremely rapid growth rates are not as critical.

publications from the USA (e.g., NAS 1979a,b, 1980, 1981, 1983a,b,c, 1984) together included over 100 species which have potential as fuelwood/bioenergy crops. Other authors have made partial inventories, e.g., for the Northern Hemisphere (Lavoie and Vallee 1981). In these publications emphasis was placed on species suitable for growing as fuelwood for individual family and village requirements; but species suited to cultivation in bioenergy plantations for domestic fuelwood and charcoal, fuelling small industries and crop drying (e.g., tobacco and tea drying, brick and tile kilns, molasses manufacture) and electricity generation were also included.

In the remainder of this section a set of about 35 of the better known species (Table 3) is used for illustration purposes. Additional information on these species can be found in Davidson (1985a) and NAS (1980, 1983a,b,c) as well as the other references given in Table 3.

Species suitable for bioenergy plantations normally should have the following attributes:

i. capacity for rapid growth on a wide range of sites (e.g., pioneer species)
ii. ability to produce wood of high specific gravity, even when grown rapidly in short rotations, i.e., high above-ground biomass production per stem and per unit area of land
iii. high wood calorific value (related to ii. above)
iv. stem and crown architecture enabling fast growth to be maintained at very close tree spacings over short rotations of about 4–8 years
v. high solar energy conversion efficiency (related to i above)
vi. good coppicing ability

While attributes ii and v have little connection with possible ecological problems, the remainder potentially have such interactions and these aspects will be discussed in the relevant subsection.

TABLE 3
Alphabetical list of trees and shrubs used as examples in this paper

Botanical name	Common name	References
Acacia auriculiformis	Australian Acacia	Little 1983; NAS 1979b, 1980; Evans 1982; Webb *et al*. 1980; Davidson 1985a
Acacia catechu	Khayer	Evans 1982; Davidson 1985a
Acacia mangium	Mangium	NAS 1979b, 1983a; Davidson 1985a
Acacia nilotica	Babul	Little 1983; NAS 1980; Evans 1982; Davidson 1985a
Albizia lebbek	Kala Koroi	Little 1983; NAS 1979b, 1980; Webb *et al.* 1980; Davidson 1985a
Albizia procera	Jat Koroi	NAS 1979b; Davidson 1985a
Artocarpus heterophyllus	Breadfruit, Jackfruit, Kathal	FAO 1982a; Davidson 1985a
Azadirachta indica	Neem	Little 1983; Anonymous 1963; NAS 1980; Evans 1982; Webb *et al.* 1980; Davidson 1985a
Cajanus cajan	Pigeon pea, Arhar	Little 1983; NAS 1980; Davidson 1985a
Calliandra calothyrsus	Calliandra	Little 1983; NAS 1979b, 1980, 1983b; Davidson 1985a
Cassia siamea	Minjiri	Little 1983; NAS 1980; Evans 1982; Webb *et al.* 1980; Davidson 1985a
Casuarina equisetifolia	Casuarina, Yar, Australian Pine, Jau	NAS 1980, 1984; Little 1983; Evans 1982; Webb *et al.* 1980; Midgley *et al.* 1983; Boland *et al.* 1984; Davidson 1985a
Dalbergia sissoo	Shisham	NAS 1979b, 1983c; Street 1962; Troup 1921; Little 1983; Davidson 1985a
Derris indica	Saw, Kerong	Little 1983; NAS 1980; Davidson 1985a
Emblica officinalis	Amloki	Little 1983; NAS 1980; FAO 1982a, Davidson 1985a
Eucalyptus brassiana	Cape York Red Gum	NAS 1983c; FAO 1979; Boland *et al.* 1984; Davidson 1985a
Eucalyptus camaldulensis	River Red Gum	Skolman 1983; Little 1983; NAS 1980; Evans 1982; Eldridge 1975; FAO 1979; Webb *et al.* 1980; Boland *et al.* 1984; Davidson 1985a
Eucalyptus citriodora	Lemon-Scented Gum	Little 1983; NAS 1980; Evans 1982; FAO 1979; Webb *et al.* 1980; Boland *et al.* 1984; Davidson 1985a
Eucalyptus deglupta	Kamarere	NAS 1983c; Fenton *et al.* 1977; FAO 1979; Davidson 1977; Evans 1982; Webb *et al.* 1980
Eucalyptus globulus	Blue Gum	FAO 1979; Skolmen 1983; Rinehart and Standiford 1983; NAS 1980; Webb *et al.* 1980, Boland *et al.* 1984
Eucalyptus grandis	Flooded Gum	FAO 1979; Skolmen 1983; Little 1983; NAS 1980; Evans 1982; Webb *et al.* 1980; Boland *et al.* 1984
Eucalyptus tereticornis	Forest Red Gum	FAO 1979; Little 1983; NAS 1983c; FAO 1979; Hillis and Brown 1978; Bell and Evo 1982; Webb *et al.* 1980; Boland *et al.* 1984; Davidson 1985a
Eucalyptus urophylla	Timor Mountain Gum	FAO 1979; Evans 1982; NAS 1983c; Campinhos 1980; Fenton *et al.* 1977; FAO 1979; Hillis and Brown 1978; Martin and Cossalter 1975–76
Gliricidia sepium	Gliricidia, Mexican Lilac	Little 1983; NAS 1980; Davidson 1985a
Gmelina arborea	Gamar	Little 1983; NAS 1980; Evans 1982; Webb *et al.* 1980; Davidson 1985a
Leucaena leucocephala	Ipil-Ipil	IDRC 1983; Little 1983; NAS 1979a; NFTA 1982; Brewbaker 1980a,b; Webb *et al.* 1980; Davidson 1985a
Melia azedarach	Paradise tree, Bakain	NAS 1980, 1983c; Anonymous 1963; Gupta 1958; Street 1962; Little 1983; Davidson 1985a
Moringa oleifera	Ben, Sajina	FAO 1982a; Davidson 1985a
Paraserianthes falcataria	Moluccana	Little 1983; NAS 1979b, 1973; Domingo 1980; Fenton *et al.* 1977; Gerherds 1976; Evans 1982; Davidson 1985a
Samanea saman	Saman, Randi Koroi	Webb *et al.* 1980; NAS 1979b; Davidson 1985a
Sesbania bispinosa	Dhaincha	Little 1983; NAS 1980; Davidson 1985a
Sesbania grandiflora	Bakphul	Little 1983; NAS 1979b, 1980; Davidson 1985a
Sesbania sesban	Sesban	NAS 1983c; Davidson 1985a
Syzygium cumini	Jam	Little 1983; NAS 1980; FAO 1982a; Davidson 1985a

Note: Neither the list of common names nor the references are exhaustive. There are other important trees used for fuelwood such as *Guazuma ulmifolia*, *Alnus acuminata*, *Alnus nepalensis*, *Inga* spp., *Bursera simaruba*, *Diphysa robinioides*, *Spondias purpurea* and *Yucca elephantipes* used in agroforestry combinations and live fencing.

5.1.1 Species having a capacity for rapid growth on a wide range of sites

Data are available on size (stem wood volume) growth for many species presently used in bioenergy plantations (e.g., Davidson 1985a).

Fastest growth under favourable site and climatic conditions is exhibited by *Eucalyptus deglupta*, *Paraserianthes (Albizia) falcataria*, *Leucaena leucocephala*, *Eucalyptus camaldulensis*, *E. grandis*, *E. urophylla*, *Acacia mangium*, *Eucalyptus tereticornis*, *E. globulus* and *E. brassiana* (mentioned roughly in decreasing order). Slowest growth is found with species such as *Acacia catechu* and *A. nilotica*., irrespective of site quality. Thus there are inherent differences between genera and between species in capacity for rapid growth on an optimum site.

Inherent vigorous growth can cause problems under certain circumstances. There is a risk of invasion of indigenous floras (Elton 1958) by aggressive exotic legumes and other trees. Some trees have also demonstrated that they can easily become weeds outside plantations. Examples are *Azadirachta indica* introduced to Africa from Asia and spread by birds into indigenous woodlands and *Casuarina* sp and *Melaleuca* sp introduced into Florida, USA which have clogged waterways there.

More and more species, some little known, are being listed as suitable for planting (Burley and von Carlowitz 1984, Burley and Stewart 1985). Introductions of exotics and reintroductions should be closely scrutinized by specialist groups such as the Working Group on Introductions and Reintroductions of the Commission on Ecology, IUCN, so that risks are minimized of later invasions of local plant communities or agricultural lands by aggressive, woody, pioneer species.

5.1.2 Species with ability to produce wood of high specific gravity

Among the lightest of plantation grown-woods are *Paraserianthes falcataria* and *Eucalyptus deglupta*; among the heaviest are *Acacia catechu*, *Casuarina equisetifolia*, *Eucalyptus tereticornis*, *E. citriodora* and *E. globulus* (Fig. 7).

Fast growth and low specific gravity are not necessarily correlated, though some of the species with the more dense wood do tend to produce lighter wood when grown rapidly under short rotations. Reasons for this include a change in structure of the wood laid down e.g., more vessels, and, on a whole-tree basis, a greater proportion of less dense sapwood to more dense heartwood in young, fast-grown trees.

An important aspect for conservation of land resources is that, all other factors being equal, high wood density means a greater weight of wood per stem and per hectare of growing space, in turn leading to less land being required under plantation to produce a given tonnage of biomass.

5.1.3 Species having wood of high calorific value

Species having wood in the highest part of a fairly narrow range of calorific values include: *Samanea*

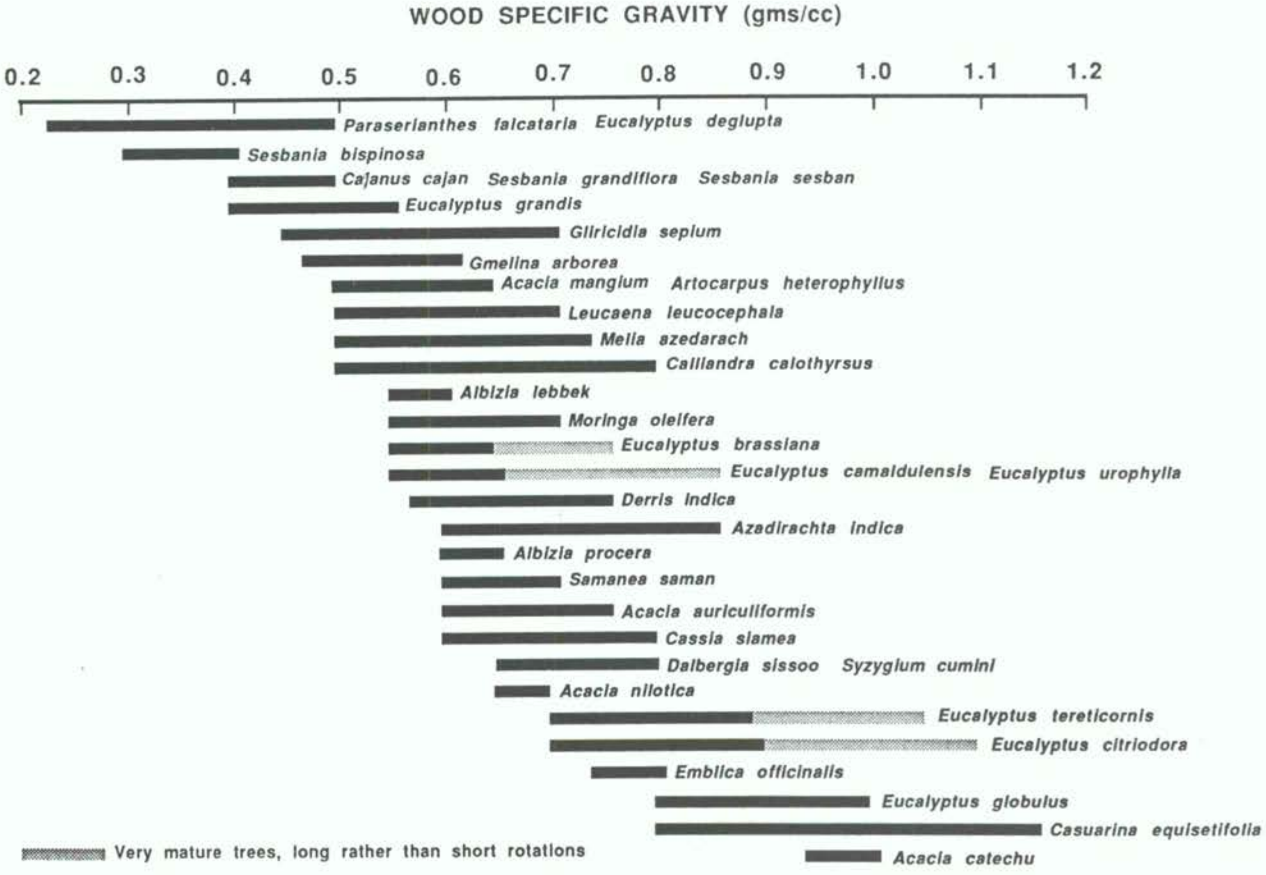


Fig. 7. Within- and between-species variation in wood specific gravity.

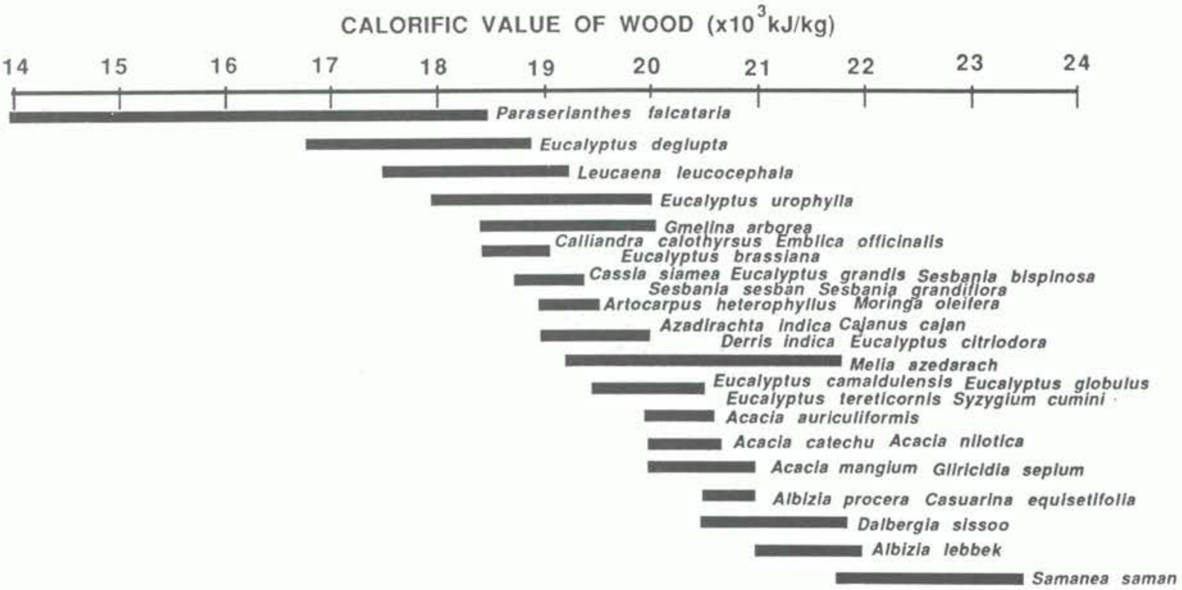


Fig. 8. Within- and between-species variation in wood calorific value.

saman, *Albizia lebbek*, *Dalbergia sissoo*, *Albizia procera*, *Casuarina equisetifolia*, *Gliricidia sepium*, *Acacia mangium*, *A. nilotica*, *A. catechu*, *A. auriculiformis*, *Eucalyptus camaldulensis*, *E. tereticornis* and *Melia azedarach* (listed roughly in decreasing order). In the lowest part of the range are *Paraserianthes falcataria* and Eucalyptus *deglupta*. In the middle are *Leucaena leucocephala*, *Eucalyptus urophylla* and *Gmelina arborea* (listed roughly in increasing order) (Fig. 8).

A similar argument to that given in section 5.1.1 can be used, in that the more kilojoule-equivalents harvested per unit area, the less land is required for a given eventual output of energy.

5.1.4 Stem and crown architecture

The wide range of above-ground biomass production shown for species given in Fig. 9 results in part from differences in planting density. Close spacing of individual stems is necessary to achieve very high yields in a short time of 4–8 years.

Only those species with single, slim, upright, straight trunks and narrow columnar crowns tolerate well the closer spacings (down to 1 × 1 m and below). *Eucalyptus* spp. *Casuarina* spp and *Sesbania grandiflora* are among the outstanding examples. Species which have a habit of producing multiple straight stems from a single stump can also produce very high yields. Examples are *Leucaena leucocephala*, *Calliandra calothyrsus* and *Eucalyptus* spp, especially after the first cutting cycle (coppice).

5.1.5 High solar energy conversion efficiency

The best species are *Sesbania grandiflora* and *S. sesban*, *Eucalyptus camaldulensis*, *E. urophylla*, *E. tereticornis*, *Casuarina equisetifolia*, *Dalbergia sissoo* and *Leucaena leucocephala* on appropriate sites (Fig. 6). The poorer species include *Paraserianthes falcataria*, *Eucalyptus brassiana* and *Cassia siamea*, irrespective of site quality. Among the visible characteristics determining solar energy conversion efficiency are crown architecture and size, and numbers, arrangement and orientation to sunlight of leaves.

5.1.6 Coppicing ability

One of the most essential attributes for trees grown in bioenergy plantations is the ability to coppice repeatedly from the cut stump. This is mainly because of the high cost of establishing the seedling generation when large numbers of plants per unit area are required. If the seedling rotation can be followed by four or five coppice cycles the costs of establishment are spread over a greater period of time. The first coppice rotation usually grows much faster than the seedling rotation because of the large root system already in place. Relative coppicing abilities are indicated in Table 4. Raising several generations by coppice means that soil is not disturbed as often for planting seedlings and the fully developed root systems help ensure soil stability on slopes until a tree cover is re-established.

Good coppicing ability is sometimes correlated

TABLE 4
Coppicing ability

EXCELLENT:
Calliandra calothyrsus
Derris indica
Eucalyptus brassiana
Eucalyptus camaldulensis
Eucalyptus citriodora
Eucalyptus grandis
Eucalyptus globulus
Eucalyptus tereticornis
Eucalyptus urophylla
Gliricidia sepium
Gmelina arborea
Leucaena leucocephala

GOOD:
Acacia mangium
Albizia lebbek
Azadirachta indica
Cajanus cajan
Cassia siamea
Melia azedarach
Moringa oleifera
Paraserianthes falcataria
Samanea saman
Sesbania bispinosa
Sesbania grandiflora
Sesbania sesban
Syzygium cumini

FAIR:
Acacia catechu
Acacia nilotica
Albizia lebbek
Albizia procera
Dalbergia sissoo
Paraserianthes falcataria
Syzygium cumini

POOR:
Acacia auriculiformis
Acacia catechu
Acacia nilotica
Artocarpus heterophyllus
Casuarina equisetifolia
Emblica officinalis
Eucalyptus deglupta

Note: Some species are listed more than once where they have a wide range in coppicing ability.

with ease of striking by vegetative propagation, meaning that some species can spread rapidly by rooting of vegetative fragments which fall on the ground or are used as stakes or fence posts, making them potentially very invasive of areas outside their natural range.

5.2 Seeds of good quality

Seeds used in bioenergy plantations should be of the highest genetic and physiological quality, since even small genetic gains in growth rate and stem weight of individuals are multiplied many times because of dense spacing.

Over hundreds of years human beings have greatly improved their food crop plants by the selection of desirable individuals as the source of seeds for the next crop, then vegetatively multiplying these plants or producing new strains by controlled crosses. During the last three decades, many tree improvement programmes have been started on the same lines. The knowledge and experience accumulated (Wright 1962, Zobel and Talbert, 1984) provide a good basis for planning new programmes and for correctly re-orienting established ones. To meet the large requirement of seeds of high genetic quality for bioenergy plantations it is imperative to conduct screening programmes for both exotic and native species and select the best seed origins (provenances).

In the developed countries a great deal of time and effort have been devoted to understanding the physiological processes involved in seed germination and seed longevity, particularly for agricultural crops. These investigations receive wide publicity and there are several specialized journals devoted to disseminating the results (such as "Seed Science and Technology" for example). However the findings are often applied in other countries to new species with little or no local applied research to backup the empirical knowledge derived overseas upon which the advances and new technology were based. Much of the imported technology, therefore, often leads to poorly planned procedures and questionable conclusions and frequently reveals that huge amounts of time and effort have been wasted.

With new Seed Centre and Seed Bank projects now starting or already under way in several developing countries, there has been a rapid increase in interest in forest seed biology, particularly in the tropics and subtropics. However, despite this interest, and the fact that a few seed centres such as the Latin American Seed Bank, have been in operation for as long as 20 years, only a very small proportion of the total number of tree species potentially of use in bioenergy plantations has yet been the subject of detailed biological and physiological studies.

There is, therefore, a need for *in situ* and *ex situ* conservation of the gene resources of these species, a matter already addressed by IUCN. IUCN can play a major role in ensuring gene resource conservation (Davidson 1983b) and integrity of stored gene resources in the form of seeds and tissues (Davidson 1986a).

As an alternative to using seeds, vegetative propagation of selected individuals can be practised. Rapid progress has been made in the use of cuttings for routine establishment of forest plantations and increased yields have resulted (e.g., Brandao *et al*. 1984).

5.3 Matching species to sites

Apart from the usual factors such as temperature and annual rainfall and its seasonality, other factors which should receive consideration are soil moisture requirements and drought resistance, soil pH, soil nutrition, susceptibility to browsing by animals and to fire, tolerance of saline soils and disease and pest susceptibility. In the tropical highlands susceptibility of species to frosts has to be considered.

5.3.1 Soil moisture requirements and drought resistance

In an earlier section it was stated that commercial bioenergy plantations should have, preferably, a productivity of over 20 tonnes/ha/yr of dry above-ground woody biomass. The well-known species which have the capacity to achieve this rate are

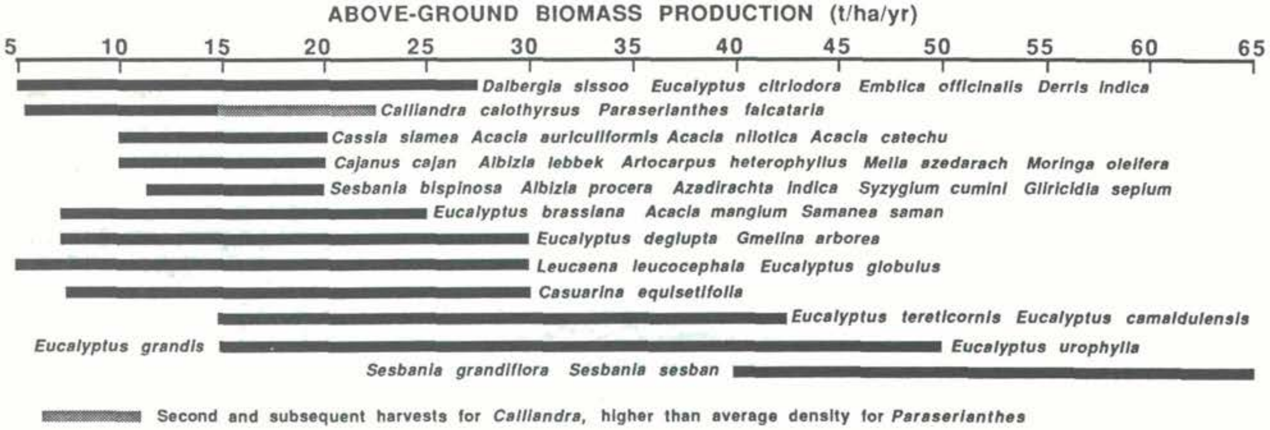


Fig. 9. Within- and between-species variation in above-ground biomass production.

limited to a couple of *Sesbania* spp, a small number of *Eucalyptus* spp some *Casuarina* spp and *Leucaena leucocephala*, on appropriate sites, in the humid tropics (Fig. 9).

For high productivity, commercial bioenergy plantations normally should be established in areas having an annual rainfall of not less than 1000 mm and preferably greater than 1250 mm (Table 5). If rainfall is seasonal with a marked dry period of four or more months, annual rainfall should allow for recharge of the aquifer to provide groundwater during the dry months.

Establishment of plantations in drier areas such as the Sahel will result in slower biomass production over longer rotations and/or restriction on the range of species from which to choose (Table 5). While lower productivity may be acceptable in woodlots destined for domestic fuelwood use, it is not always acceptable for ensuring continuity of supply to fixed-location, commercial units such as those used for thermal electricity generation.

Water use by *Eucalyptus* plantations has been a controversial subject particularly in India. Available scientific evidence indicates eucalypts have no more effect on the water table than several other species of commonly planted trees and on the basis of unit weight of dry biomass produced, eucalypts are relatively efficient in their use of water (e.g., *E. tereticornis* in Table 5) and they maintain biomass production under conditions of soil moisture stress (e.g., see Karshon and Heth 1967, Dabral 1970, Banerjee 1972, Thomas *et al*. 1972, George 1978, Chaturvedi 1983, Tiwari and Mathur 1983, Ram Prasad *et al*. 1984, Rawat *et al*. 1984, Davidson 1985b, Poore and Fries 1985). Provided adequate land and water surveys are carried out and resources allocated proportionally to tree crops, agriculture and water conservation, ecological problems associated with eucalypts will be minimized.

Species choice will be affected according to whether a site has too much water or too little or whether or not there is a prolonged dry season, because species differ in their tolerance to waterlogging or drought (Table 6). Soil texture and bulk

TABLE 5
Theoretical water consumption by bioenergy tree plantations in rainfall equivalent (mm/yr)

Species	Water consumed per unit of biomass produced (litres/gm)*	Water consumption (mm/yr) for different levels of biomass production					
		10	15	20 (tonnes/ha/yr)	25	30	35
Eucalyptus tereticornis	0.48	480	720	960	1200	1440	1680
Syzygium cumini	0.50	500	750	1000	1250	1500	1750
Albizia lebbek	0.50	550	825	1100	1375	1650	1925
Acacia auriculiformis	0.72	720	770	1440	1800	2160	2520
Dalbergia sissoo	0.77	770	1155	1540	1925	2310	2695

* Source: Chaturvedi, 1983; Tiwari and Mathur, 1983 (these data were obtained from experiments conducted by the Research Laboratory of the U.P. Forest Department, India and actually apply only to specific and controlled laboratory experiments where measured doses of water were given periodically to young plants; extrapolation to trees and stands, as has been done here, should be accepted with caution, the main point being made is the relative differences between species).

TABLE 6
Species tolerance to a range of soil moisture regimes

SPECIES TOLERANT OF FLOODING, WATERLOGGING

Casuarina equisetifolia
Eucalyptus camaldulensis
Sesbania bispinosa
Sesbania sesban

SPECIES PARTICULARLY INTOLERANT OF FLOODING, WATERLOGGING

Azadirachta indica
Cajanus cajan
Leucaena leucocephala

SPECIES PREFERRING SOME SOIL MOISTURE ALL YEAR ROUND

Albizia lebbek
Albizia procera
Emblica officinalis
Paraserianthes falcataria
Sesbania grandiflora
Syzygium cumini

SPECIES TOLERANT OF DRY WEATHER

Acacia mangium
Artocarpus heterophyllus
Azadirachta indica
Calliandra calothyrsus
Gliricidia sepium
Leucaena leucocephala

SPECIES VERY TOLERANT OF A LONG DRY SEASON

Acacia auriculiformis
Cassia siamea
Dalbergia sissoo
Eucalyptus citriodora
Eucalyptus tereticornis
Gmelina arborea
Samanea saman

SPECIES TOLERANT OF PROLONGED DROUGHT

Acacia catechu
Acacia nilotica
Casuarina equisetifolia
Eucalyptus brassiana
Eucalyptus camaldulensis

density (degree of compaction) are also important factors and soil working alone can improve the performance of the plantation.

Too high a rainfall, e.g., over 4000 mm/yr, can cause problems too for seedling establishment such as local waterlogging and puddling of soil. Constant cloud cover in areas of very high annual rainfall reduces growth rate by reducing photosynthesis.

5.3.2 Soil pH

One of the most critical factors in matching species to site is soil pH. Soils in the tropics and subtropics have a wide pH range, from extremely acid (e.g., pH 3.8–4.9 in some heavily leached hill soils under *Imperata cylindrica* grass) to mildly alkaline (e.g., pH 7.0–7.5 in some river terrace soils with lime concretions) and to very alkaline soils (e.g., pH over 8.0 in limestone and some littoral soils).

Below pH 5.5 very few tree species grow well (Fig. 10). Among these, the eucalypts and acacias are particularly adapted to acid soils. *Acacia auriculiformis* has one of the widest ranges of pH tolerance of any documented tree species in the world (pH 3.0–9.5). *Calliandra calothyrsus* also tolerates well the acid soils. Some well-known species, such as *Leucaena leucocephala*, have a very narrow pH tolerance in the neutral to alkaline range (Fig. 10). It grows poorly when soil pH is less than 6.0 and will usually fail to produce adequate biomass on more acid soils (pH less than 5.5) (Davidson 1985a). Some progress has been made in breeding acid-soil-tolerant varieties of *Leucaena* and other species.

5.3.3 Nutrition

On fertile soils, using the latest production technology and mechanization, very high biomass yields have been obtained for tree crops, even in temperate countries (Nilsson and Zsuffa 1983). However, in the less developed, highly populated, tropical regions, such soils, where found, normally have been or will be devoted to intensive food production (Fig. 6).

Most likely, the land available for tree biomass production will be the poorer, degraded lands, including "forest fallows" which totalled 228 million hectares in the broadleaved forest areas of 76 tropical countries in 1980 (Lanly 1982).

The Commission on Ecology, IUCN, has already addressed the problem of reforesting degraded tropical forest lands (Lovejoy 1985). Since then other agencies, e.g., FAO (Sumitro 1985), have studied the problem. Soil texture and bulk density are important in initial seedling establishment. Many of the degraded soils have become compacted and would require soil working to improve seedling survival rates but this must be done in such a way as to minimize the possibility of erosion on slopes, e.g., by working along the contours.

Ability to fix nitrogen is important in establishment of trees on degraded soils. Atmospheric nitrogen is fixed through a symbiotic relationship, usually with the bacterium *Rhizobium* in nodules on the roots (Hamdi 1982). *Acacia mangium* and *Sesbania grandiflora* often have very large root nodules (over 1 cm in diameter) on seedling roots growing in polythene bags in the nursery. However, the size and abundance of nodules may not be a reliable indication of the quantity of nitrogen being fixed. *Casuarina* spp. also form large root nodules (NAS, 1984) but the root symbiosis is with *Frankia* spp., a filamentous soil actinomycete. Species with the ability to fix nitrogen are listed in Table 7.

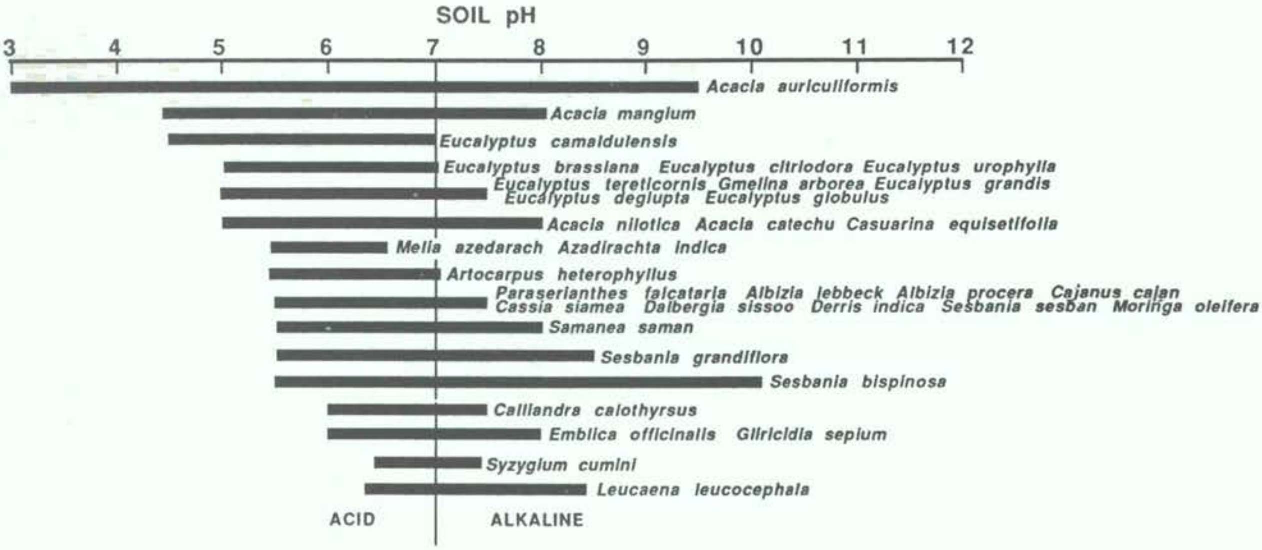


Fig. 10. Within- and between-species variation in tolerance to soil pH. Soil pH is one of the critical factors to be considered in matching species to sites.

In plantations of species which do not fix nitrogen, such as *Cassia siamea* and *Eucalyptus* spp., the underplanting of leguminous shrubs or groundcovers may make up for the disadvantage (Davidson 1986b), though this is not always true, since in some systems there may still be a net loss of nitrogen (Schubert 1982, Wigston 1985).

For those species which do not fix nitrogen, low nutrient demand is important. Several species of eucalypts and pines have low nutrient demand which accounts for their usually successful establishment on nutrient-poor sites, where other species, particularly native moist forest species, have failed. Mixed plantations of *Eucalyptus* and leguminous trees may be more productive than pure stands (De Bell *et al*. 1985), though silviculturally compatible mixtures are difficult to design and establish, since one or two species tend to dominate while others are suppressed.

TABLE 7
Atmospheric nitrogen-fixing ability

SPECIES WITH NITROGEN-FIXING ABILITY

Acacia auriculiformis
Acacia catechu
Acacia mangium
Acacia nilotica
Albizia lebbek
Albizia procera
Cajanus cajan
Calliandra calothyrsus
Casuarina equisetifolia
Dalbergia sissoo
Derris indica
Emblica officinalis
Gliricidia sepium
Leucaena leucocephala
Paraserianthes falcataria
Samanea saman
Sesbania bispinosa
Sesbania grandiflora
Sesbania sesban

SPECIES LACKING THE ABILITY TO FIX NITROGEN

Artocarpus heterophyllus
Azadirachta indica
Cassia siamea
Eucalyptus brassiana
Eucalyptus camaldulensis
Eucalyptus citriodora
Eucalyptus deglupta
Eucalyptus grandis
Eucalyptus globulus
Eucalyptus tereticornis
Eucalyptus urophylla
Gmelina arborea
Melia azedarach
Moringa oleifera
Syzygium cumini

A question that has been raised by ecologists and foresters is whether high productivity can be maintained in the long term on the same site (Carlisle and Chatarpaul, 1984). This is an important question, because it is the large, short-term yields that will encourage the planting of new bioenergy plantations and make the practice more attractive than exploiting more intact natural forest in the tropics. Unfortunately most of the yield data given in the literature are for natural forests and first rotations, and very few data are available for yields in successive cycles, so no certain answer can be given (Chijicke, 1980). Evans (1976, 1980, 1982) has reviewed this aspect, including the effects of climatic change, genetic differences, site changes due to carrying out intensive plantation forestry and biological and silvicultural differences and the available evidence of changes in productivity in successive rotations. He concludes (1982) with the statement:

> "What meagre evidence exists suggests that serious declines in productivity with successive crops will not be an immediate problem on most sites. Nevertheless, short rotation fast-growing plantations in the tropics are more akin to farming than much traditional forestry, especially as practised in temperate countries. The forester may have to learn from the farmer the importance of regular inputs – intensive cultural practise, fertilizing, genetic improvement – to ensure that productivity is maintained."

A mixed plantation of *Eucalyptus saligna* and *Paraserianthes falcataria*, a non legume and legume respectively, established by the Bioenergy Development Corporation, Hawaii.

However, Evans' view of the second and subsequent rotation problem dealt primarily with plantations having rotations which are now considered "long", 12–15 years or more, rather than the "short" rotations advocated for bioenergy plantations of 4–8 years, rarely longer.

Very short rotations would be a different situation and nutritional deficiencies could develop more rapidly. The main reason for this is that the stems of young trees consist mainly of sapwood and this can have a much higher nutrient content than heartwood (Crane and Raison 1980). The nutrients removed from the site by successive harvests of such plantations can greatly exceed that from a single harvest of larger trees grown over the same period (Raison 1984). The situation is worse if bark is also removed from the site, since this usually has a higher nutrient content than stemwood.

It seems likely heavy inputs of fertilizer will be required to compensate for nutrient losses during harvest, even on fertile soils. On poor soils fertilizer application will be necessary from the beginning to achieve the high growth rates required of bioenergy plantations, and to assist tree seedlings in overcoming weed growth.

5.3.4 Susceptibility to browsing

Nearly all species that may be used in bioenergy plantations are susceptible to browsing by livestock, particularly goats, during the first year of growth. Exceptions include the eucalypts, *Azadiracta indica* and some *Cassia* species. Even eucalypt leaves and young shoots are eaten by starving cattle during droughts. In areas of high human population there is nearly always intense pressure to find grazing land and livestock quickly find their way, or are deliberately herded, into unsupervised plantations.

Eucalyptus saligna bioenergy plantation, Hawaii. The combined access road and firebreak, as well as the area for a considerable distance into the plantation, have become covered with a creeping legume, *Calopogonium* sp. This has suppressed the *Imperata* grass and other weed competition and presumably is contributing nitrogen to the soil.

More research is required on browsing susceptibility. Sometimes simple measures, such as, for example, splashing wet cowdung over young *Acacia mangium* plants and letting it dry on the leaves, deters cattle from browsing during dry weather. Normally stock has to be kept out of the young plantations by using live fencing (e.g., *Ipomea*, some species of *Erythrina*, *Cajanus*), posts and wire (including live posts such as *Bursera simaruba*, *Diphysa robinioides*, *Spondias purpurea* and *Yucca elephantipes*, which are planted as large cuttings, up to 2.5 m long, and thus sprout beyond the reach of browsing cattle), or by employing herders.

As an alternative, fodder can be grown along with the trees and cut for stall or tethered feeding. Once tree canopies are above the reach of stock, grazing usually can be allowed among the trees, provided the density of the stand is such that sufficient light reaches the ground to support a living ground cover. Species with open crowns such as some *Eucalyptus* spp. (e.g., *E. camaldulensis*) allow much light to reach the ground even at densities up to 10,000 stems/ha.

5.3.5. Fire tolerance

Fire tolerance is difficult to classify. Factors involved are the degree of protection offered to the terminal shoot by surrounding organs or tissues and the thickness of bark shielding the cambium. Most species can be killed by fire during their first year of growth. The intensity of the fire determines the rate of mortality and intensity depends on the amount of fuel available, topography and weather conditions prevailing at the time. A list of species tolerant to light ground fires, after the second growing season, is given in Table 8.

The deciduous and semi-deciduous species (e.g., *Acacia catechu*, *Albizia lebbek*, *Albizia procera*, *Azadirachta indica*, *Cajanus cajan*, *Gmelina arborea*, *Melia azedarach*) are susceptible to crown fires during the dry season (dry leaves on the plants during very dry weather) and to very hot ground fires (large quantities of dry litter resulting from leaf-fall and penetration of the drying effects of wind and sunlight to the forest floor).

Some species (e.g., *Artocarpus heterophyllus*:

TABLE 8
Species tolerant of light ground fires (after the second growing season or when stems have reached about 8 cm diameter at ground level)

Acacia auriculiformis
Acacia catechu
Acacia mangium
Acacia nilotica
Albizia lebbek
Albizia procera
Cassia siamea
*Casuarina equisetifolia**
Eucalyptus brassiana
Eucalyptus camaldulensis
Eucalyptus citriodora
Eucalyptus tereticornis
Eucalyptus urophylla

* Only after rough bark has formed.

latex bark; *Azadirachta indica*: oil in seeds; *Derris indica*: oil in seeds; *Eucalyptus citriodora*: high volatile oil content in foliage) are more susceptible to crown fires during hot, dry, windy weather because of their extra inflammability.

Most eucalypts and acacias are adapted to habitats which are regularly burned in the natural state. These species have evolved with generally thick bark which protects the cambium, and have systems of dormant buds which are able to replace the foliage entirely after damage by fire (Davidson, 1985b) so have a place for planting where the fire hazard is high, though there are exceptions such as *Eucalyptus deglupta* which has very thin bark and is extremely susceptible to fire.

In tropical and subtropical regions, uncontrolled accidental or deliberately started fires are an important agent of deforestation whether the forests are natural or planted. Training in forest fire management for plantation managers must receive high priorty.

A wise precaution is to include firebreaks for protection of woodlots and plantations. These can be bare earth or "green-breaks" of non-inflammable, evergreen species of small trees or shrubs. Using close spacing normally suppresses weed growth and usually keeps the litter layer shaded and moist, reducing the fire hazard. Underplanting succulent leguminous species has the effect of hastening breakdown and incorporation of litter and prevents the rapid spread of groundfires, particularly in *Eucalyptus* plantations.

Very fierce, hot fires usually destroy the forest crop, the understorey and litter layers and associated flora and fauna. One way that the severity of a fire can be reduced is by periodic fuel reduction burning, called "controlled burning". However, this aspect has been inadequately researched except in a few temperate countries, notably Australia.

5.3.6 Tolerance of soil salinity

Very few of the species listed in Table 3 are tolerant of saline soil conditions. Among the exceptions are *Casuarina equisetifolia*, *Derris indica*, *Eucalyptus camaldulensis* (certain provenances), *Sesbania bispinosa* and *Sesbania sesban*. Increasing effort is being directed to breeding for improved tolerance to soil salinity.

5.3.7 Disease and pest susceptibility

One of the most serious potential risks to bioenergy plantations is the possibility of destruction owing to pests and diseases.

Ecologists have stressed that substitution of natural forest by even-aged plantations of only one or two species may remove many of the factors restraining local tree pests and pathogens, thus increasing the risk of attack from them. Man-made forests in the tropics and subtropics are often cited as being much more affected by disease and pest epidemics than those in temperate regions (Bassua 1979, Uhlig 1979) and large numbers of pests and diseases have been reported as attacking plantations (Browne 1968, Lamb 1974, Gibson 1975, 1979, Johnson 1976a,b, Sen-Sarma and Thahur 1983, Sehgal 1983).

Nevertheless, several successful plantation schemes have been documented over the last two decades (Gibson and Jones 1977, MacDonald 1983) and it is becoming increasingly evident that the risk to plantations has often been overstated, despite the fact that adoption of monocultures has led to an increase in the number and severity of diseases and pests (Gibson and Jones, 1977). Much of this increase has stemmed from the method of clearing the prior forest, poor matching of species to sites and the new ecological conditions created in plantations because of intensive management rather than the individual susceptibility of a single tree species (Gibson, 1980).

It has been pointed out by van Emden and Williams (1974) that mixed species plantations (artificially created diversity) do not necessarily improve ecological stability, and are certaintly still inferior to naturally occurring closed forests in regard to species diversity.

In many bioenergy plantations recently introduced exotic species are used. This trend is increasing, and their success, and frequently unexpected very rapid growth, is often due to an absence of insect predators and pathogens, particularly where previously non-forested areas are being planted. Widespread success of *Eucalyptus* outside Australia is attributed by Pryor (1976) to the absence of numerous leaf eating insects found in their native environment. However, by the same reasoning, it can be argued that the natural agencies of biological control operating on these pests are also absent, should such a pest be introduced. Gibson and Jones (1977) have noted most exotic species have a period of relative freedom from organic damage, but this does not last indefinitely. For example, there are now numerous pests of eucalypts in Brazil and more are being discovered, whereas there were almost none reported early this century.

Evans (1982) has set out the biological risks associated with plantation ecosystems and plantation forestry practices. Gibson (1980) attributes the generally good health of industrial plantation forests throughout the world to the better opportunities for disease and pest protection in intensively managed plantations, but, so far, the best examples of such plantations are in temperate countries, such as New Zealand, not in the tropics.

In the case of bioenergy plantations there is the opportunity to choose genetically resistant stock. Testing a variety of species and provenances for resistance to local pests and diseases is an important first step if two to three years of lead time are available. Exotics normally should be chosen only when they are markedly superior to local species in disease resistance (experience has shown they are nearly always superior in biomass production). The operational use of a small number of species simplifies investigations of host-parasite relationships and hence rapid identification and control of the problem. Very short rotations used in most bioenergy plantations also reduce risks of pests and diseases spreading, since the trees are often harvested before the invading organisms reach plague proportions. The intensive management and regular, compact shape of most bioenergy plantations and woodlots facilitates monitoring of stand performance and control of any pests and diseases.

6. YIELDS AND ECONOMICS OF BIOENERGY PLANTATIONS

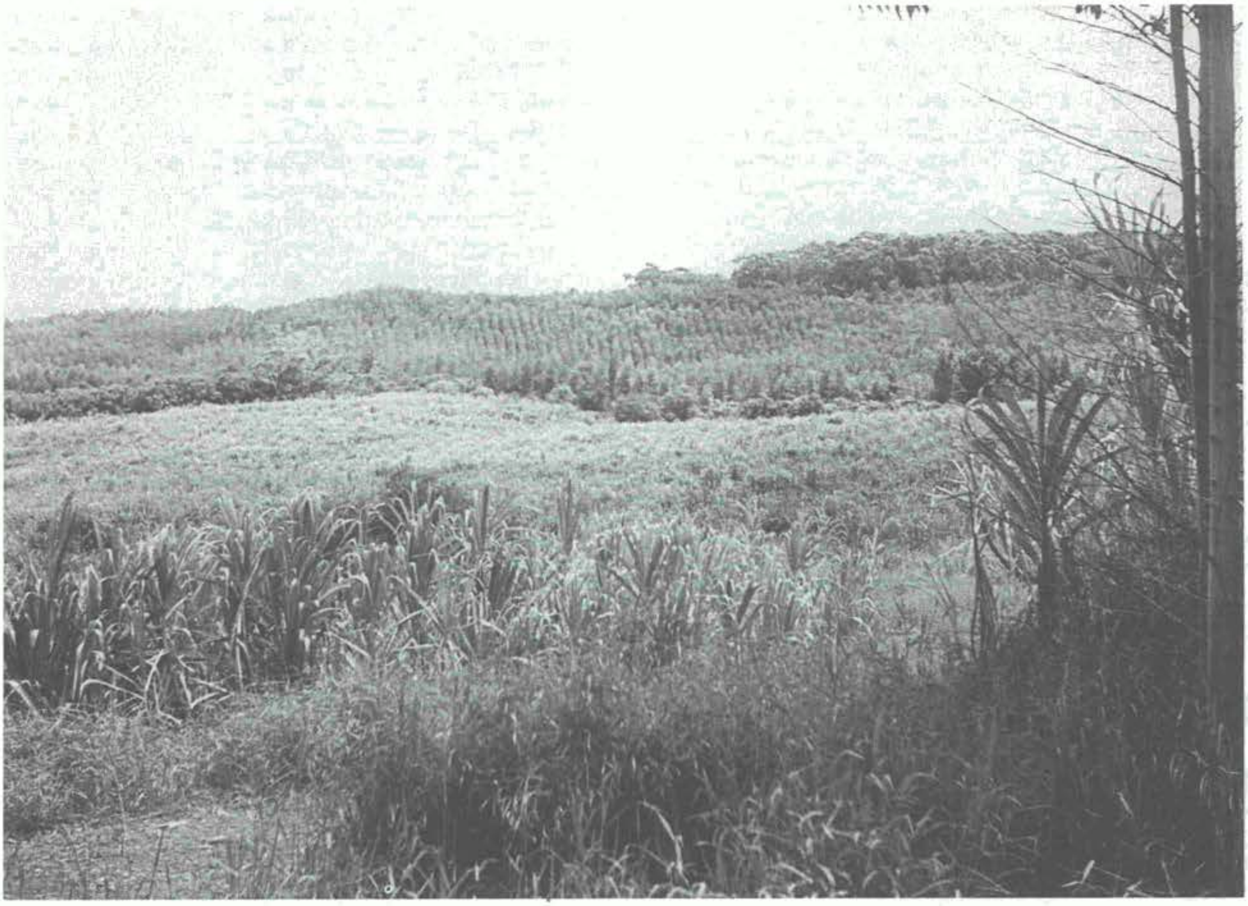
Since McAlpine *et al*. (1966) put forward their ideas on 'Silage Sycamore' and Young (1964, 1968) exposed his views on complete tree utilization, the concept of short rotation, high density plantation forestry has been pursued with increasing vigour. One reason for this has been that rising cost of land has made growing trees for 40–60 years unduly expensive (Ribe 1974). Ribe (1974) and Cromer *et al*. (1975) reviewed the first decade of work, when pulp was considered to be the major candidate for end use (Schmidt and DeBell 1973). However, in the late 1970's, with a change in emphasis, these types of plantations came to be called high density, biomass or energy plantations. Yields of 12–25 dry tonnes/ha/yr over 4–10 yr cycles collectively exceeded by 3–4 times those achieved over one 30–80 year cycle, because advantage was taken of early and high current annual increments in a succession of juvenile stages, whereas, usually, mean annual increments of long and short rotation crops could be expected to be about the same, irrespective of spacing. Spacing, and thinning, become more important where fuelwood production is combined with the production of large logs for sawing (Harrick and Brown 1967, Einspahr and Benson 1968, Steinbeck *et al*. 1972, Young 1972, Ralston 1973, Schmidt and DeBell 1973, Ribe 1974, Bowersox and Ward 1976, Mariani and Mariani 1978, Mariani *et al*. 1978, Gibson 1978, Whitmore 1980, Srivastava *et al*. 1982). Cannell (1982) has reviewed world forest biomass and primary production data over a wide range of species, sites and management conditions.

Some European countries with low indigenous energy supplies, such as Sweden and Northern Ireland, are developing energy biomass schemes involving plantations of rapidly growing trees, but which require added nitrogen to achieve adequate yield in short rotations. The main species used in these programmes are from the genera *Salix* (willows) and *Populus* (poplars). These can give very high rates of biomass return. For the Swedish project the break-even point has been calculated in terms of thermal oil equivalent at 12 tonnes/hectare/year (Koster *et al*. 1981). Swedish trials are achieving 12–18 oven dry tonnes/ha/yr (Nilsson and Zsuffa 1983, Wigston 1985).

The California Department of Forestry established a Wood Energy Programme in 1978 (Standiford and Ledig 1983a). By 1983 it had two major projects investigating the use of *Eucalyptus* and other fast-growing species for fuelwood plantations. Following a mandate given in 1980, nine plantations throughout the State were established, mainly in 1982, under a Biomass Tree Farms Project (Brittner 1983). Norona (1983) analysed the factors involved in setting up large-scale *Eucalyptus* energy farms and power cogeneration in California and some preliminary work has been done on the economics of such farms (Standiford and Ledig 1983b), showing some of them to be profitable at yields of about 20–22 tonnes/ha/yr green biomass at relatively low stockings of 640–1010 trees/ha but much higher yields are possible using high density, short rotation culture (Sachs and Low 1983). In 1982 there were 13 biomass cogeneration facilities in California with 15 more projected (Pacific Gas and Electric 1982). The California Energy Commission has a goal of meeting 5 per cent of the State's energy budget by the year 2000 from biomass energy production (Pillsbury and Ayers 1983).

In California some trial plots of *E. grandis* have yielded 22 oven dry tonnes/ha/yr at close spacing (17,200 stems/ha) and short rotations (6 months). *E. camaldulensis*, planted at 12,550/ha over a two-year rotation, has produced 37 oven dry tonnes/ha/yr (Sachs and Low 1983). It must be remembered that the high yields quoted by these and some other US bioenergy studies have been extrapolated from small plots grown under the influence of continental summers with long hot bright days, and abundant soil moisture on fertile or fertilizable soils.

Szego and Kemp (1973) estimated a 400 megawatt (MW)/day power station could operate on



Abandoned sugar-cane land is being used for bioenergy plantations in Hawaii. The wood is being mixed 50:50 with bagasse to provide fuel for electricity generation.

a softwood plantation of 96,000 hectares based on a yield of 13 m³/ha/yr. Another study on *Alnus rubra* having a stem and branch productivity of 34 oven dry tonnes/ha/yr showed that an area of 17,000 ha was required with a rotation cycle of 10 years to sustain a 1540 MW/day power plant (Evans 1974).

These results from already established bioenergy plantations, mainly in temperate countries, support the contention of White and Blaskett (1981) and Pearce (1983) that with short cycle, narrowly spaced coppice systems using fast-growing species, it is possible to achieve a productivity of more than 20 dry tonnes/ha/yr on 4 to 8 cycles, and these yields are obtainable with already available genetic material in temperate climates and on land too poor for agricultural crops. Yields could be expected to be better following genetic manipulation (Kapoor and Sharma 1984) and planting of fast-growing species in warmer and more humid climates or on better soils.

Higher yields from more productive species (Ledig and Linzer 1978, Gurumurti and Raturi 1982, Davidson and Das 1985, Rockwood *et al*. 1984) growing in the tropics and subtropics would require much less land area (Table 9). Even if the productivity value shown in the example given in Table 9 was halved to 12.5 dry tonnes/ha/yr, requiring double the total area, or 3180 ha, the area of land required is still relatively small. However, up to the present time, very few data have become available in order to assess realistically the performance of bioenergy plantations in the tropics and subtropics.

Among the best performances in tropical countries are those given by Ek and Dawson (1976a,b) of 40 dry tonnes/ha/yr for *Populus*, Frederick *et al*. (1983) 22.6 dry tonnes/ha/yr for *Acacia dealbata* and Akachuku (1981) 30 dry tonnes/ha/yr for *Gmelina arborea*, but these data were probably from small trial plots given abundant water and fertilizer.

It is necessary to look at a couple of major forest plantation schemes, one in Brazil and one in the Congo and smaller examples from Hawaii, Philippines and India to gain an idea of the potential for large scale bioenergy plantations in the tropics.

Aracruz Florestal SA is a privately-owned forest company in northern Espirito Santo State in Brazil (19°S) which has established some 60,000 ha of eucalypt plantations to provide raw material for

TABLE 9
Bioenergy plantation area requirement for a power plant with generation capacity of 100 MW/day

ASSUMPTIONS:

i. Calorific value of air-dry wood at 15 per cent moisture content = 15,500 kJ/kg = 15.5×10^6 kJ/tonne.
ii. Use of fast-growing species (e.g. *Casuarina equisetifolia*, *Eucalyptus camaldulensis*, *Sesbania grandiflora*) at 12,345 plants/ha initial spacing rotation cycle 5 years, mortality 20 per cent.
iii. Yield of dry woody biomass = 25 tonnes/ha/yr.
iv. Conversion efficiency of wood – fuel thermal power generation = 25 per cent.
v. Efficiency of power plant equipment overall = 85 per cent.

CALCULATIONS:

i. Energy value of the wood = $15.5 \times 10^6 \times 0.25$ kJ/tonne
= 3.88×10^6 kJ/tonne
= 10.8×10^2 kWh/tonne (IJ = I watt/second)
ii. Power generation value of the wood = $10.8 \times 10^2 \times 0.85$ kWh/tonne
= 9.2×10^2 kWh/tonne
iii. Daily woody biomass requirement for 100 MW/day = 109 tonnes
Yearly woody biomass requirement for 100 MW/day = 39,785 tonnes
iv. Yearly area plantation required = 318 ha (yield 125 tonnes/ha after 5 years). Plant five blocks each of 318 ha each year (total 1590 ha plus access roads, etc.) the first block yielding 39,785 tonnes harvested at the end of the 5th year, dried for use at the end of 5 years 6 months, then continuous harvesting and replanting thereafter.

pulping, but branches and tops are also used for energy production. In 1974, as part of a tree improvement programme aimed at increasing yields and producing more homogeneous planting material, Aracruz started a research programme on mass vegetative propagation of *Eucalyptus*. The first commercial planting of one million cuttings was made in 1979. The number planted increased successively: 3.5 million in 1980, 10 million in 1983, 14 million in 1984 and now essentially 100 per cent of the company's planting programme of over 15 million plants/yr.

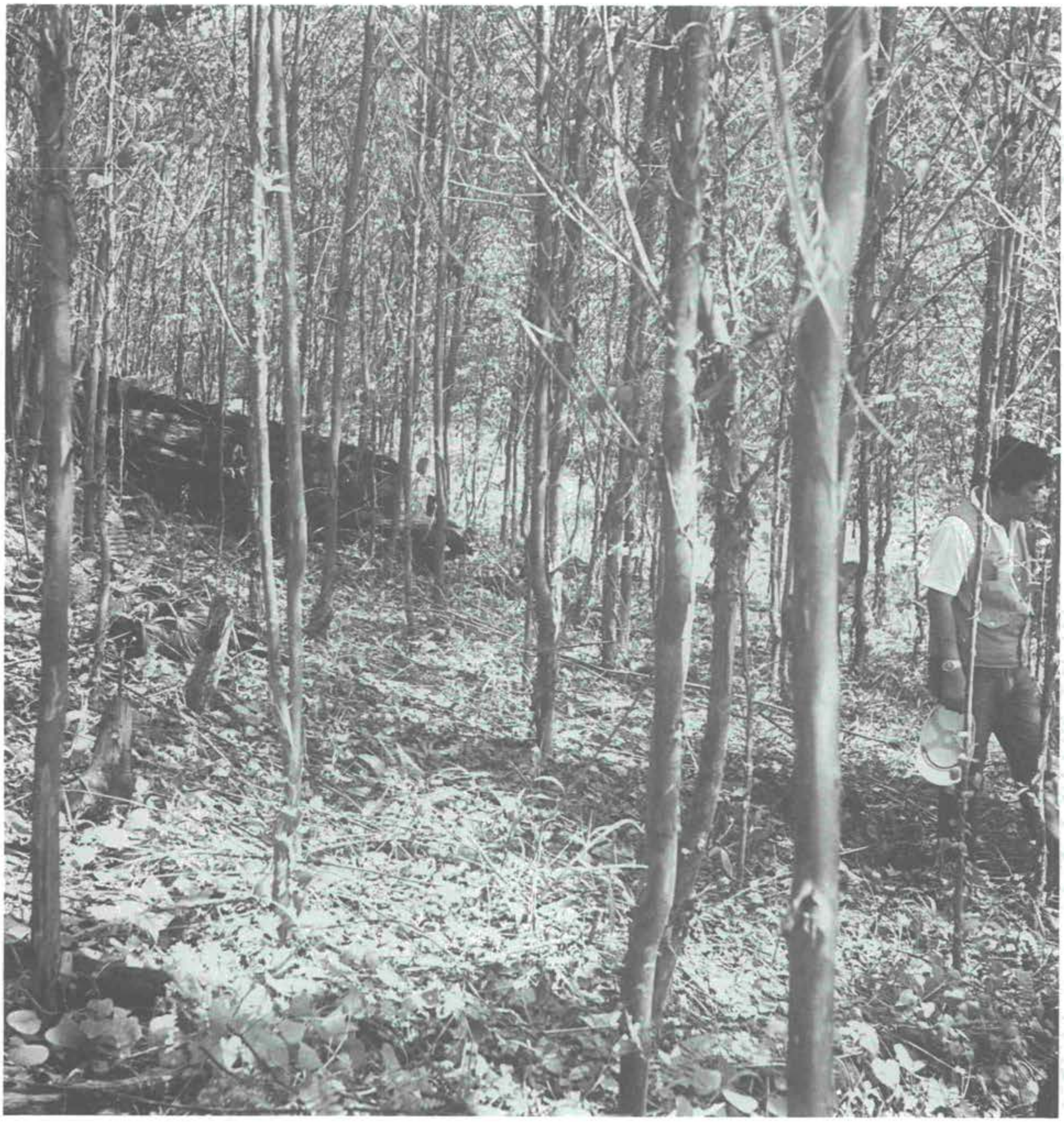
Gains made through the use of clonal material at Aracruz have been spectacular. Average yield increment has increased 112 per cent, from 33 to 70 m^3/ha/yr of stemwood, while average wood density has increased by 25 per cent, from 460 to 575 kg/m^3, both figures calculated for seven year old plantations (Brandao *et al*. 1984, Wallenberg Foundation 1984). This represents a stemwood biomass production of 40 tonnes/ha/yr at 3 × 3 m spacing (1111 stems/ha) under intensive culture (ploughing, fertilizing and weeding).

Research plots five and half years old at Aracruz show additional gains which could take routine production to 110 m^3/ha/yr using cuttings of *E. grandis* × *E. urophylla* hybrids (Wallenberg Foundation 1984). Assuming no further gains in wood density, this represents 63 tonnes/ha/yr of stemwood and near 80 tonnes/ha/yr production of total biomass above ground.

Pulpwood plantations at Pointe Noire (5°S) in the Congo, exceeded 15,000 ha by 1984. These plantations are also clonal, the clones have been derived from hybrids of several eucalypt species. The growth rate of monoclonal plantations of two of the better hybrids on the savanna sands at Pointe Noire in 1983 was 30–35 m^3/ha/yr, at age 6 to 7 years (Delwaulle and Martin 1983). This was a remarkable improvement over the 12 m^3/ha/yr obtained there in the 1960's with *E. tereticornis* (12 ABL) (Chaperon 1984) and 20 m^3/ha/yr in stands of selected provenances of *E. urophylla* (Delwaulle and Martin 1983) and *E. cloeziana*. These results represent an above ground biomass production of over 25 tonnes/ha/yr. Recently selected clones from control-pollinated hybrids are growing even faster.

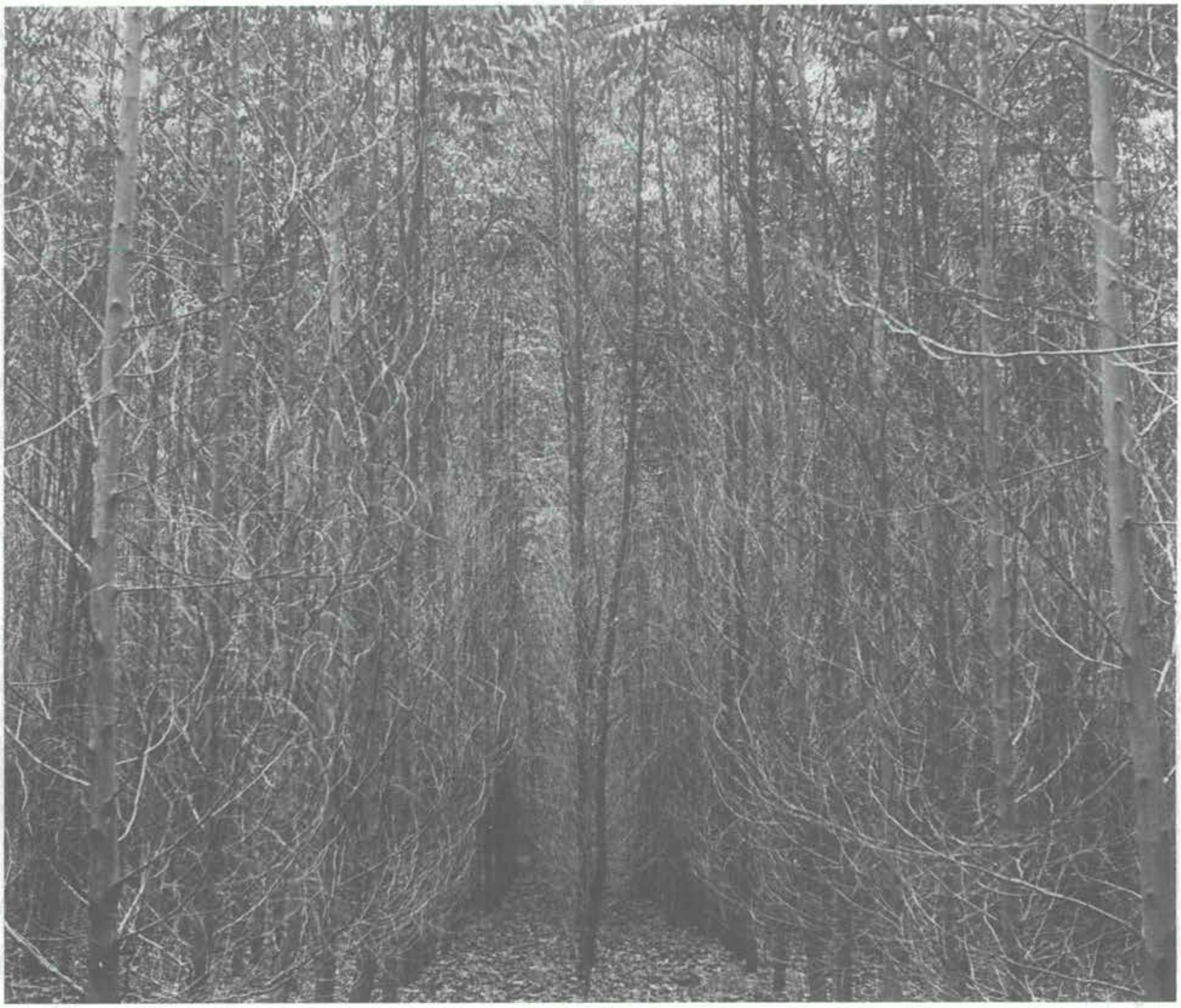
In Hawaii there has existed a need for additional domestic energy sources to reduce dependence on imported oil and to supplement existing supplies of biomass fuel (mainly sugar cane bagasse in the past). To date the most promising source of additional biomass fuel is woodfibre supplied from fast growing, man-made energy plantations (Bioenergy Development Corporation 1983, 1984). The biomass energy equation anticipated following recent measurements at about half rotation age on stands several hectares in extent is that about 20 ton/ac/yr (51 tonnes/ha/yr) green weight of wood (equivalent to 20 barrels of oil) on a 6 year crop cycle will be produced for mixing with bagasse (50:50) to provide feedstock for electricity generation in existing power plants.

Wood energy from biomass for rural development has been under study in the Philippines for more than a decade (Denton 1980, 1983), much of the biomass is intended to come from purpose-planted fuelwood plantations (Semana and Bawagan 1979, Wiersum 1982). There have been a number of dendrothermal projects set up for electrification of rural areas. By 1984 six sites had been set up using British and French assistance, with plans to have 20



High-density planting trials of *Eucalyptus deglupta*, Mindanao, Philippines. This species grows rapidly but coppices poorly and the wood produced is of low density and probably more suited for use as pulpwood rather than fuelwood.

sites with a total capacity of 60 MW/day by 1990. Each site consists of a power unit with 3 MW/day generation capacity surrounded by 1000 ha of land in 10 modules of 100 ha. Each module provides the livelihood for 10 families initially given housing and loans to become settled. *Leucaena leucocephala*, *Cajanus cajan* (Pigeon Pea) and hill rice are the main crops grown. Three planting methods are used for the *Leucaena*; seedlings, direct seeding and stump or bare-root planting. This species has grown well on alkaline soils derived from coral and yields of 20 dry tonnes/ha/yr have been achieved of small size round material (1–10 cm diameter, 75 cm long). In 1984 this was selling at US\$6/stacked m^3 (0.75 m^3 solid) at the household door. Each electricity generation plant cost between 2 and 3 million dollars to build and plantation costs were 300–500,000 dollars for a 1000 ha site. Problems encountered have been sulphur deficiency in the calcareous soils and poor growth of *Leucaena* and fire problems on acid grass-



High-density trials of *Eucalyptus saligna* in Hawaii. Trees in the left and right foreground are about 1.5 metres apart, while those in the background, with the insertion of an extra row midway between the wider spacing, have a reduced spacing of about 0.75 metres.

land soils. The constraints could be reduced by choosing a more appropriate tree species for those sites.

Experimentation on bioenergy plantations has been under way in India for some time (Chakrabarti 1984) and lately also in Bangladesh (Centre for Policy Research 1982). India's first bioenergy plantation project has just commenced generating electricity at Khandia Village in Gujarat State. Two turbines have been set up to generate a total of 30 kW/day, sufficient to meet the full requirements of the village at a cost less than oil or coal fired plants. Elsewhere four larger plants capable of generating 1 MW/day are being built. It has been estimated that about 1000 ha of plantations grown on 4–7 year rotations can provide fuelwood or charcoal for 125–150 families and 3 MW/day of electricity.

The Gujarat Fuelwood/Agroforestry/Social Forestry experience has been well documented. It is one of the best examples of farmers spontaneously responding to cash market incentives for fuelwood, poles and other forest products which had become scarce. A government programme that provided subsidised seedling and extension support promoted a four fold increase in planting rate, from 12 to 48 million trees/year for the years 1975 to 1979. The rate doubled again to 100 million trees/year by 1981 and almost yet again to 195 million trees per year by 1983. Based on a state population of about 15 million this represents a planting rate of 13 trees/person/year and the equivalent of 150,000 ha of plantation had been planted by the end of 1983. Of a total 5-year project cost of US$76 million, of which US$37 million was met by a World Bank loan, investment in staffing costs, research training and

A bioenergy plantation of *Eucalyptus saligna* about five years old in Hawaii. Similar stands have yielded up to about 25 tonnes per hectare per year of dry, above-ground biomass. The yield is expected to be greater from plantations established at much closer spacings than this which is relatively wide at about 2.5 × 2.5 m.

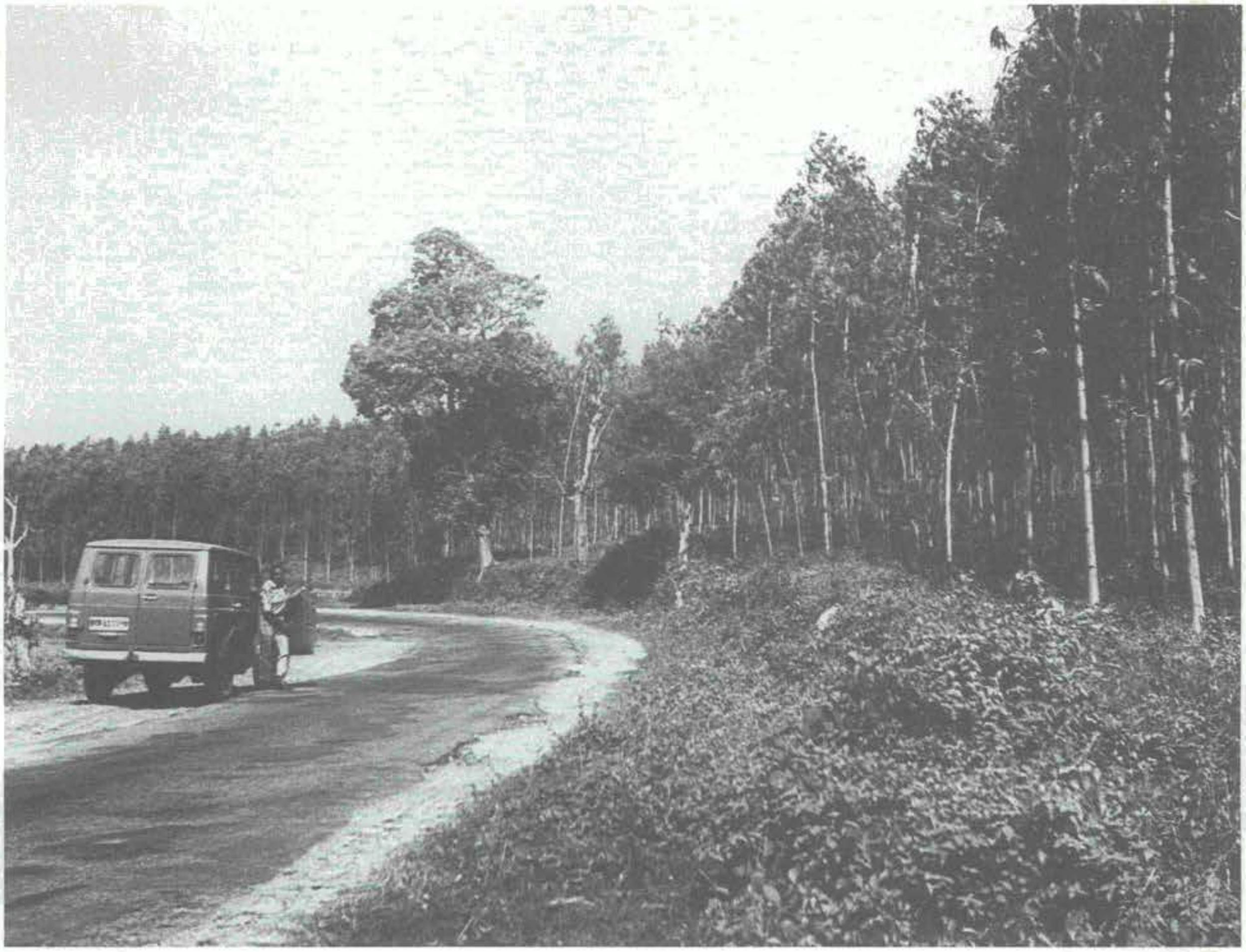
fellowships took up 25 per cent. The economic rate of return for the project was 15 per cent. Some individual farmer's financial returns were in the range of 20–30 per cent (Spears 1985).

Investment by the World Bank, Asian and African Development Banks in forestry now exceeds US$1.5 billion in 50 countries. This investment has covered a wide range of forestry activities such as watershed protection, fuelwood, social/agroforestry, anti-desertification projects, protection of threatened tropical forest ecosystems, forestry research, education, training and extension. In practise, many of the agroforestry/social forestry/community forestry and environmental protection projects financed by the development banks have earned considerably higher economic rates of return (15–30 per cent) than industrial forestry projects (10–15 per cent) (Spears 1985). While there have been some notable project failures in the forestry sector, given appropriate pricing, land tenure policies and institutional support, most projects have performed satisfactorily (Spears 1985). Projects which include financial incentives for large numbers of people to plant small numbers of trees per person seem to have a good chance of success.

7. BIOENERGY PLANTATIONS AS BUFFERS TO AID NATURE CONSERVATION

High density energy plantations, many of which can be managed for pulp and reconstituted wood products, posts and poles as well as for fuelwood, have the potential to relieve the pressure on the world's remaining natural forests, particularly tropical moist forests (Lanly 1982), even when they are some distance away from such forests. They could be used also as buffer strips around reserved and preserved areas to reduce encroachment in densely populated regions.

The buffer could be a physical one and operate in two directions. It could for example, if properly designed, with very close spacing, adequate depth



Another example of a buffer plantation of *Eucalyptus camaldulensis* in Bangladesh. This one is two-and-a-half years old and averages over half a kilometre in depth. It is located between a heavily travelled road and valuable natural Dipterocarp and bamboo forests and high value timber plantations behind.

and suitable species, keep elephants and other large animals in a reserve and away from nearby villages and crops. If extensive enough, the buffer would allow gathering of fuelwood and building materials and perhaps some grazing and some hunting to be carried on under the trees, reducing to a minimum the requirement for humans and domestic stock to enter the reserve.

Perhaps an ecological use of dense plantations, particularly as monocultures, could be to create an artificial "sea" around "island" reserves. Many of the current ideas about reserve size and shape have been based on theories developed from studies of island biogeography (Diamond 1975, 1976; Simberloff and Abele 1976, Terborgh 1976). They assume the "sea" contributes nothing to the "island" but, in many cases, this might not be true on land. Secondary and degraded forest areas, surrounding intact forest, particularly those areas invaded by weeds and pests, may contribute seeds and organisms to the intact forest "island" which could interfere with normal ecological processes within a reserve, such as at the stage when an individual tree dies (gap dynamics, Webb *et al*. 1985). A dense plantation could act, in this context, as a sterile barrier.

There have been some successful demonstrations of buffers. One is in Kenya where buffer plantations, backed up by vigorous Forest Department action to enforce nature reserve boundaries, have made it possible to protect unique tropical rainforests in the Kakamega region for many years despite the very high population pressure in nearby areas.

8. SOCIAL AND INSTITUTIONAL CONSTRAINTS

Virtually no forest land areas in the tropics and subtropics, whether covered by intact forest, or lying as forest fallow, grassland or degraded land, are now free from current or *de facto* past occupants and users. Where poor results have occurred in plantation projects carried out so far, they can be largely attributed to local social and institutional constraints and land tenure problems rather than to technical or silvicultural failures.

A forest plantation project cannot be implemented in isolation, it will be greatly affected by its surroundings. Where a forest area is being diminished by the impact of a high population, a man-made reforestation project will need to be "more about people than about trees" (Office of Technology Assessment 1984). Social assessment must take place before, or at least in parallel with, resource, environment and economic assessments.

Methodologies for social and institutional assessment have been assembled over the last decade by development agencies (FAO 1978, World Bank (Moranka 1980), USAID 1982). These methods mainly apply to project appraisal. Monitoring and evaluation of the social impacts in projects after they have started are still in their infancy (e.g., Government of India 1983) reflecting the great difficulty in designing methodology effectively to carry out such monitoring.

Land tenure problems are a major reason why land resources are not used wisely in the tropics and subtropics (Land Tenure Center/ICRAF 1985). Communal lands and lands alienated by governments cause the most concern. The problem is greater where customary law and its institutions has grown weak and state laws are ineffective because of remoteness from the influence of central government, manipulation by vested interests and red tape surrounding local administration. Such serious constraints must be eliminated, however difficult this may be; and social assessment methods may help a new generation of professional planners overcome the problems.

Ways need to be examined in which people, who are likely to suffer negative impacts because of a project, are compensated. Exchange of land is possible. Monetary compensation is becoming common, particularly in countries such as Indonesia, though the introduction of cash compensation is expensive, and opens another avenue for spurious claims and fraudulent dealings.

There is a great need for rural sociologists and ethnologists to determine the structure and degree of institutional development at the village, clan and tribal levels and ensure that motivation occurs at these levels. In the allocation, replenishment and conservation of natural resources there are always issues such as national versus local interests, immediate use for cash versus long-term conservation and forestry versus agriculture. Clear policy objectives need to be formulated and supporting legislation drafted to ensure that local people and organizations contribute towards the general good as well as to their own needs (FAO 1985).

Another constraint which detracts from the success of intensive forest plantation projects is that many trained foresters in the tropics and subtropics are not well equipped with the necessary technical and communication skills. The abilities of typical field officers who are required to operate at the most risk-prone stages, from seed handling to harvest of the plantation, must be improved.

Most of the foresters now in executive control are from a generation of "conservators of forest" who have been charged with the responsibility of exploitation of national forest estates for timber and other products. Some may have experience in conservative forest plantation schemes involving long rotations of 50–80 years. Very few have the breadth of experience in seed and propagation technology, species selection, tree improvement and breeding and short rotation, intensive silviculture and management techniques required, for example to:

i. Carry out land and site classification, capability and suitability assessments (FAO 1976, 1984, Carpenter 1981, Davidson 1983, Hamilton 1983).
ii. Establish suitable locations for bioenergy plantations, in relation to all other competing uses.
iii. Carry out comprehensive species testing.
iv. Select a small number of the best species and carry out detailed provenance investigations to determine the best seed sources within those species (Burley and Wood 1976).
v. Move early to set up internal seed stands for the best provenances.
vi. Carry out a tree improvement programme (Zobel and Talbert 1984) to produce better seeds for future planting, once an area of plantation of a single good provenance has been established.
vii. Use proper silvicultural techniques for establishment and intensive management of plantations based on up-to-date knowledge (Evans 1982, FAO 1979).
viii. Ensure necessary research is put in place early to cover possible required changes in management, harvesting and utilization techniques. This may require additional funding for forest research institutes and for educating scientists (World Bank and FAO 1981).
ix. Continuously monitor plantations for dealing in a timely fashion with any adverse environmental effects on the site or downstream or the incidence of pests and disease on the trees.

In addition, many foresters are not willing to communicate or are not well equipped with the necessary communication skills to deal with rural people in a manner which will ensure their participation in forestry projects.

Lack of modern technological and communication skills implies a need for restructuring and reorienting forest management institutions and changing curricula in forestry education programmes. Only in a very few countries in the tropics and subtropics have these changes begun.

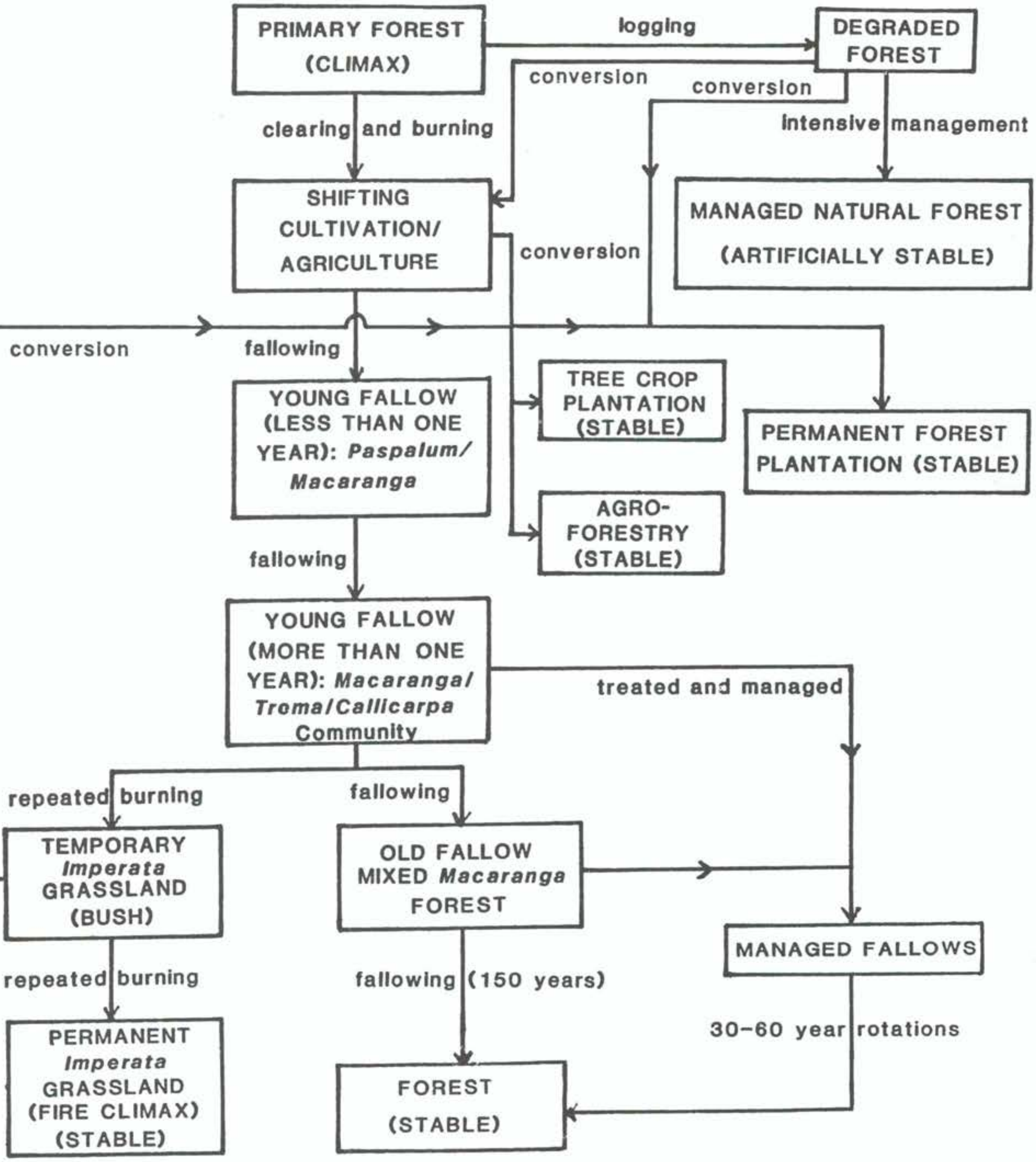
9. ALTERNATIVES TO INTENSIVELY MANAGED BIOENERGY PLANTATIONS

Bioenergy plantations are not the only option which could redress the energy shortfall in a region while at the same time providing other benefits such as buffering conservation areas or bringing degraded forest lands back under tree cover.

Intensity of management and level of inputs or treatments will depend on the local objectives of management, the present condition of the land, location and accessibility and environmental factors. There are more than one pathway to wise and stable use of tropical forest land (Fig. 11).

Conflict of land use is more frequent where population density is high and quality of land is good. Technology helpful in the management of conflicting interests in forest land resources has gained much attention, resulting in effort being increasingly directed to "social forestry", agroforestry and its many variations, and "forests for local community development" (FAO 1978, Arnold 1983, Douglas 1983).

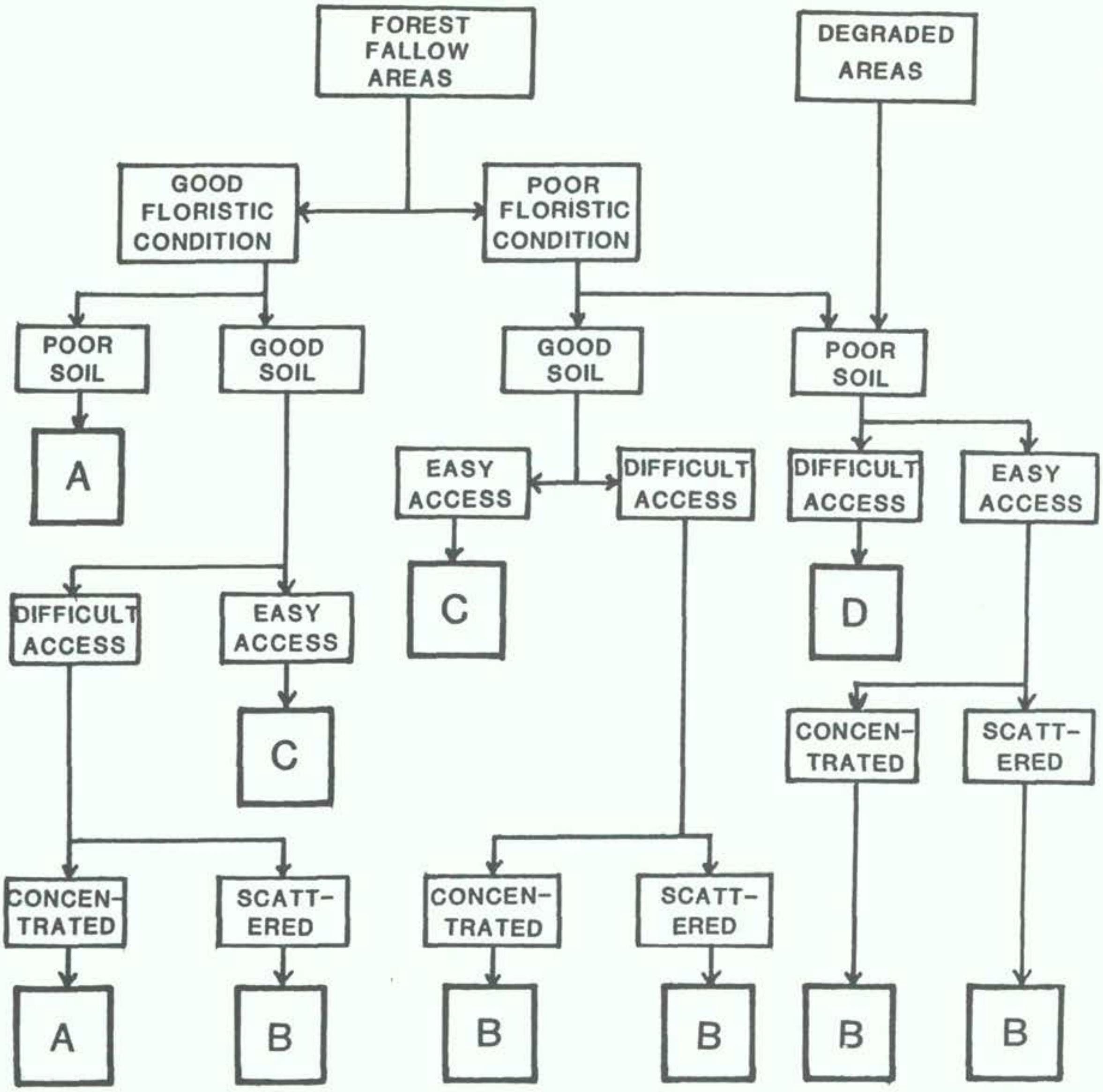
A dense planting of *Cajanus cajan* between widely spaced *Tectona grandis* (Teak) trees. Dense *Imperata* grass formerly occupying this site has been almost totally suppressed. There are many hundreds of varieties of *Cajanus cajan* including the tall, woody shrubs shown here and others over four metres high resembling small trees when grown at wider spacing. This legume provides fuel from the stems, an edible pulse from the seedpods and the leaf litter improves the soil.



Source: Modified from Sumitro (1985)

Fig. 11. There are many pathways to a stable ecosystem in tropical forest areas. Conversion of exhausted areas of shifting cultivation and *Imperata* grasslands to tree crop plantations, agroforestry or permanent forest plantations, including bioenergy plantations, are among methods of increasing ecosystem stability where this stability is lacking.

Until freely available supplies from natural forests are almost exhausted, fuelwood farm gate prices in many developing countries are likely to remain too low to trigger large scale spontaneous private investment in free-standing energy plantations (Spears 1985). Nevertheless, much fuelwood can and is being produced as an integral component of multi-purpose agroforestry or industrial forestry programmes. Twenty-two forestry projects with fuelwood components have been financed by the World Bank during the last five years. None of these projects would have been economically viable had



A - Treat forest fallows with supplemental tree planting

B - Establish bioenergy plantations

C - Use agroforestry techniques

D - No treatment until after A, B and C have been taken up

Source: Altered from Sumitro (1985)

Fig. 12. Floristic condition, soil fertility, degree of access and spatial distribution of areas to be planted are among the factors affecting the decision on the technique to be used for plantation establishment.

fuelwood production alone been the main objective. However, combined with sales of other forest products (poles, pulpwood, timber), all of these projects demonstrated acceptable economic rates of return and 66 per cent of total physical output was fuelwood (Spears 1985).

Using agroforestry as one way to tackling the fuelwood crisis also has positive implications for increasing agricultural productivity. A decision-making process for incorporating agroforestry into programmes of rehabilitation and use of forest fallows and degraded areas is given in Fig. 12. There are already numerous examples of multiple-purpose trees that are planted in part for bioenergy purposes but also serve as live fences, shade trees for coffee, tea and cocoa and also are planted around houses and on farms or in gardens. There is a large body of literature available on agroforestry. Much of this information comes from the Centro Agronomico Tropical de Investigacion y Ensenanza (mostly in Spanish) for the tropical Americas and from the International Council for Research in Agroforestry (mostly in English) for Africa and elsewhere.

From the point of view of risk management it is better to have a diversified set of forestry activities in a region – small scale (Ffolliot and Thames 1983) and large projects; several types of species (hardwood, softwood, fast growing, slow growing); different types of forest (natural, timber plantation, bioenergy plantation, agroforestry) and flexible end uses (different rotation lengths and harvesting methods for fuelwood, pulp, sawn timber).

10. USE OF WOOD RESIDUES AND WASTE TO SUPPLEMENT BIOENERGY PLANTATIONS

Other than purpose-planned bioenergy plantations, probably the greatest potential for immediate development of wood as a source of energy would be in wood residues (Srivastava *et al*. 1982), both those normally left behind in the forest and waste materials resulting from manufacture of wood products (Marklund 1986).

Of the standing tree about 60 per cent by volume normally is removed from the forest as the merchantable log, leaving behind the stump and roots (about 23 per cent) and the branches and crown (about 17 per cent) (the proportions vary according to tree species and size) (Young 1968, King and Smith 1974, Marklund 1986). Additional fuel material in the form of non-commercial species, dead wood and material damaged through gaining access and in extraction of logs may be available, provided the additional costs involved in their extraction, transport and preparation can be met. There is the need also to consider other factors such as the possibility of nutrient and humus depletion and soil erosion which might result from whole-tree utilization. Some changes in forest management would be required to ensure that bark and other residues which are high in nutrient content are left at the stump.

Where land is cleared for plantations (timber trees, oil palm, rubber) or for human settlement and agriculture, the forest biomass is often incompletely utilized and a good deal of wood is burnt to waste without considering extraction for fuelwood and small scale charcoal manufacture.

In processing operations, further residues and waste products are created in the form of chips, bark, sawdust, slabs and edgings. Recovery of green sawn timber can be as low as 30–35 per cent and is rarely above 65 per cent of the true log volume under bark (the variation is due to log quality, size and sawing techniques) (Gregor 1965, Virtucio, 1970, Liversidge 1973, Ironside 1973, King and Smith 1974, Clark 1976). Of the residues produced about 10 per cent are bark, 20 per cent are sawdust and 70 per cent are slabs and edgings (i.e., solid wood pieces).

Residues are also generated by the plywood industry (only 30–50 per cent of the log ends up as plywood veneer) and from further manufacture, e.g., shavings, sawdust and sanding dusts from furniture factories.

The increasing exploitation of forests and the corresponding large quantities of unused residues are leading to increasing problems of pollution, some serious. Fouling of creeks and rivers by leachates coming from large bark and sawdust dumps is more prevalent and smoke and particulate emissions are high, arising from burning waste in the open, or from poor incineration, where mechanical devices are used. Logging residues left in the forest increase the possibility of catastropic fires such as that experienced in East Kalimantan in 1983. These problems illustrate the need for tighter environmental controls on the timber industry and, in turn, point to the positive contribution to the environment that better wood waste utilization could make. Integrated management of all operations is the best solution for the long term but, in the short term, financial rates of return will be less at first, because of the cost of implementing the necessary environmental controls.

11 DISCUSSION

National governments are becoming increasingly aware that they can only stop, or at least reduce, the damaging effects of forest depletion and subsequent land degradataion by involving the full spectrum of participants engaged in all phases of development – national and provincial government agencies, planners, non-government organizations and local people.

Increased awareness of the need for protection, and wise use of ecological resources, including forest, soil and water, has come about for several reasons. The more important are:

i. Wide publicity and acceptance of the World Conservation Strategy and follow-up programmes such as the Tropical Forests, Plants and Wetlands Campaigns of IUCN and the World Wildlife Fund.
ii. Fuelwood and oil crises of the 1970's which brought to the fore the importance of forests (and other potentially renewable resources) as a source of energy and underscored their possible use as an economic base for long-term development.

iii. Rapid and periodic assessment of changes in vegetative cover, which became available through remote sensing techniques such as satellite imagery, pointed out to the world community and national governments the disastrous trends in the depletion and degradataion of forest cover.

Historically, forest land in the dry and wet tropics was under the immediate control of local, usually tribal, people and customarily sometimes considered as communal. In modern times, state and commercial interests and modern communications have tended to push aside customary law and introduce new attitudes and values about property ownership, including land and rights to use land. Centres of control shifted to places usually remote from the land being governed, so that local abuses of land and associated resources became a new way of life for officials, usually outsiders, now charged with land management and for governing people stripped of their customary land rights. This system quickly became institutionalized, often in more than one Government Department. Little or no incentive was left to stimulate awareness among the local people about conservation, or the rehabilitation and proper use of local forest resources. In many places these pressures, combined with a rapid population increase are among the reasons why shifting cultivation and more damaging forms of slash and burn agriculture have in recent times begun to sweep away large tracts of tropical forest.

The developed world is only now recognizing these and similar institutional features, occurring in many parts of the developing world, which virtually force people to continue to destroy forest without securing a compensatory, sound, productive use either of the wood or the land (FAO 1985). Attempts to grow bioenergy plantations on fallow land should only be made if at the same time measures are taken to halt or slow down the spread of the more damaging forms of shifting cultivation. If the population pressure driving this type of shifting cultivation remains, it will only result in new areas being opened up. The human factor must therefore be an important component in all projects for rehabilitation of tropical moist forest lands.

Traditionally, local communities of shifting cultivators depended on the forests for their total life support, not only for providing patches of cultivable land, but for fresh water supplies, hunting, and gathering a wide range of products. With the arrival of a cash economy, sale of non-timber forest products and earning wages in forestry activities became important.

A study in East Kalimantan (Kuswata 1984) showed that, even among farmers on paddy rice fields near forest, many still had to look for additional income by exploiting the nearby forest, often illegally, for products such as rattan, rosin, fruit and wood for carving. They also sought employment in legal forest activities. These pressures came about because their income from the ricefield was not enough for their year-round subsistence and their labour was not fully absorbed by farming. A similar situation has been noted recently by the author in South Kalimantan where farmers in resettlement schemes, growing only dryland rice on a poor soil, cannot survive on their agricultural plot alone. The unsuccessful resettlement schemes are providing new foci for destruction of the adjacent forest.

It will be important to promote now a balanced relationship between people and forests so that forest resources can be conserved for the benefit of people in the future. The problem is how to balance the exploitation of forest products and other forest land uses with the uses of non-forest land in order to allow people to live near the forest and at the same time keep them aware of forest conservation.

Manpower is a renewable resource compared with items of expensive heavy machinery. A very important benefit of bioenergy plantations would be in creating work in rural areas at a lower investment cost than other industrial projects. The opportunity for employment, whether in sparsely or densely populated areas, plays an important role in reducing pressure on land. As many as 1000 people can be employed permanently to look after 100,000 ha of intensively managed forest plantation.

Projects are beginning to appear in national development plans for the creation of renewable resources, including the rehabilitation of depleted forest lands and degraded areas. However these projects must be well presented, with analyses showing economic, social and environmental benefits, if they are to attract development assistance. Leaders claim that the problem lies not in the availability of sufficient money, but in the absence of well presented and convincing investment proposals for forestry projects which will have positive environmental impacts. Neither land classification, followed by land suitability assessment, nor nature conservation are being adequately addressed.

Concern by IUCN and other international agencies about forest depletion and degradation arises from the fear that the rate of deforestation in the tropics and subtropics is so alarmingly high that the tropical moist forest biome will largely disappear from the earth in the not too distant future.

IUCN is worried about the global consequences of deforestation, the related reduction of the gene-pool for further plant and animal evolution and the continuing elimination of endangered wildlife and rare plant and animal species. It is also worried about possible changes in the radiation balance and carbon cycle of the biosphere and in global and regional weather patterns. Although these last concerns have not been conclusively vindicated by long-term research results, even small changes will have a bearing on long-term nature conservation.

Natural resources such as forests, soil and clean, fresh water are important for nature conservation, for the life of rural communities which depend on forest resources and, ultimately, for the future well-being of nations, because of the interdependence of trees and agriculture.

The natural regeneration of tropical moist forests cannot be relied upon for the provision of the huge amounts of fuelwood and small round timbers required in the future by expanding populations in the drier parts of the tropics (Poore 1983, Davidson 1985c). In the remaining more heavily forested parts and in the lightly exploited areas of tropical forests, provision of fuelwood from natural stands may be adequate at present; but all forecasts suggest strongly that this cannot be sustained, given the inherent low rate of productivity of these forests. The ecological complexities of their renewal and only partial scientific understanding of the complex ecosystem interactions involved in natural regeneration will make it difficult, if not impossible, to increase production from natural forests sufficiently to meet the future demands of energy from wood (Poore 1983, Davidson 1985c).

Development by all countries in the tropics and subtropics of policies and master plans for bioenergy plantations is imperative, carefully integrated with plans for natural forest management. These policies and plans should involve the establishment of large plantations in suitable areas, together with village woodlots, wind breaks, shelterbelts, plantations on roadsides, railway and canal embankments and hedgerows. Because of the usually difficult site conditions, use of self-sown species is often not feasible (Lovejoy 1985) and reliance may have to be placed on the introduction and expansion of the use of the many exotic species available. Some have been mentioned here and others have already been tested in subtropical and tropical regions. Still others offer much promise.

Not only are such developments economically and socially indispensable but they are also ecologically desirable in the long term provided they are related to the management of any remaining natural forest and to an overall strategy of development, involving rural–urban relations and improvement of agriculture.

Sufficient has been mentioned here to demonstrate that development of bioenergy plantations, particularly of exotic species, demands adequate prior appraisal of the climatic and physical environments. Maximum use should be made of data already available and simple classification of land made without recourse to complex soil surveys and detailed land evaluation so that species/site matching can be rapidly achieved over large areas by field officers.

Large-scale planting of trees will mean the gradual replacement of rotational and shifting forms of agriculture by less land-demanding and more managed farming systems involving both food crop production and tree growth (Hall and de Groot 1985). Notwithstanding this change, areas of natural and semi-natural forest will continue to be reduced because of rising population.

Many ecologists and IUCN are concerned about the destruction of ecological diversity and its replacement by much simpler ecosystem types, with consequent risks of soil erosion and further land degradation. The following points made by Moss and Morgan (1981) are relevant to this debate and are quoted here with minor additions:

i. "A major question is not just destruction of tropical forests, but what is replacing them. This seems to be a crucial issue in Amazonia. In much of Africa and Asia high forest is already replaced by low secondary forest and thicket, and occasionally by much more degraded vegetation types. There seems to be good reason to suppose that the progressive replacement of such a landscape by planted fallows, woodlots, shelterbelts and hedgerows would in fact reverse the present degenerative trend and produce a more viable and no less ecologically effective landscape. There are sound economic reasons, in terms of quality timber production, for preserving considerable areas of self-propagating forests and managing them for wood production. No doubt also some areas need to be set aside unmanaged for scientific study." The suggestion that self-propagated communities should be supplemented by planted ones is thus in no sense necessarily ecologically retrograde, provided they are set in context by a land use plan which reserves adequate areas of natural forests for nature conservation and landscape protection.

ii. "The replacement of tropical closed forests by planted communities should not be considered, apart from the correlative proposals for tree planting in both the humid and the dry savannas, and in areas of intensive agriculture. Afforestation on a considerable scale is also advocated for the driest margins, such as the Sahel of Africa. The implementation of such proposals will result in a considerable increase in the bulk of the vegetation of these areas, and a consequent improvement in their ecological status. This will more than offset the marginal losses to global cycles which may occur in relation to closed forest.

iii. "In both closed forest and savanna it will be the more degraded and more intensively used areas which will receive priority attention, since it is these which are generally associated with the highest population densities, both rural and urban. It is in such locations therefore that the demand for fuelwood is also greatest. The development of woodlots, shelterbelts and hedgerows of fast-growing exotics can only result in ecological improvement in such areas.

iv. "Ecological diversity will be maintained in terms of a diverse mosaic of heterogeneous and discrete ecosystems, rather than in the complex vertical structure of a homogeneous continuum covering very large areas. There is no self-evident reason why the latter should be preferred to the former, or should be any less ecologically viable, particularly if areas of the latter type are included within the general pattern.

v. "It seems to be important to recognize that progressive degradation of forest and grass-herb fallows is inevitable in many areas owing to increasing population numbers and to the demands created by urbanization. In such circumstances it would seem prudent to so direct the satisfaction of the energy demand that a relatively stable ecological situation be created in the landscape. Processes of change cannot be arrested, only directed."

WHAT CAN IUCN DO?

IUCN should explore the feasibility of holding a major international forest conservation and development symposium convened with the cooperation of UNEP and the World Bank, perhaps under the auspices of FAO, with a theme such as "high yielding plantations contribute to forest conservation".

IUCN can take a number of other initiatives such as promoting, though not necessarily funding, the following:

i. Preparation of effective national forest and environment legislation in those countries where this aspect is weak. Weaknesses are often in implementation and contradictory land laws rather than in the basic legislation and these problems must also be addressed. Economic incentives should be used to ensure that legislation is followed.

ii. Use of sound national and local land use planning based on land classification. Where local expertise is not available for this task, IUCN should take the lead in providing a source for such expertise on behalf of governments and bilateral and multilateral development agencies.

iii. Planting of large areas of intensively managed plantations outside remaining natural forest to reduce the exploitative pressure on these forests, particularly the tropical moist forests (compensatory plantations).

iv. Use of the huge areas of degraded lands and other lands in the tropics now devoid of forest cover, but otherwise unutilized or underutilized, for intensive tree husbandry instead of clearing more intact forest for conversion to plantations. Though yields are likely to be low in many places (as low as 5 m^3/ha/yr) this strategy could still produce social benefits for local people.

v. Research on integrating bioenergy plantations with other uses of forest land through techniques of agroforestry.

vi. Research on the long-term effects of intensive tree culture on the immediate site and the surrounding environment.

vii. Education and training, at all levels, of personnel involved in intensive silviculture and agroforestry.

viii. Upgrading facilities concerned with forests and the environment at educational, training and research institutions.

ix. Use of plantations as buffer zones around national parks and protected areas which are subject to encroachment from adjacent centres of high population.

xi. Conservation of tree gene resources both *in situ* and *ex situ* so that higher yielding varieties can continue to be assessed and added to plantation programmes.

xii. Monitoring of introductions of exotic tree species to reduce the risk that natural floras are invaded.

Most of these concepts have been expressed repeatedly for a couple of decades. IUCN must address itself to determining why there has been a lack of progress so far in implementing these ideas. Appraisal of successful tree plantation schemes and application of the principles of success in demonstration units in forest areas elsewhere seem to be the path to follow.

POLICY CONSIDERATIONS FOR GOVERNMENTS

i. Governments require, as a matter of priority, national forest and environment legislation which sets out guidelines to enable granting of forest lands to a spectrum of uses which require action from clear felling existing forests on the one hand to forest preservation on the other hand, and to reforestation or afforestation of denuded or degraded lands. IUCN has already published a series of guidelines (Poore, 1976) concerning use of tropical moist forest land, and is presently attempting to ensure they are made more relevant and effective (Davidson 1986, in press).

ii. Within a framework of sound forest and environmental policies, land use planning is required firstly on a national basis, then followed up later with district or provincial plans and, lastly by local plans (i.e. always working from the whole to the part rather than the reverse). National land use planning might be received more favourably internationally if it also took into account the global and regional status of the forest biome and the availability of wood products, rather than operating in isolation.

iii. National interests have to be balanced against the interests of special groups in the community during strategic land use planning. In many countries land tenure and land availability will constrain Governments from establishing large bioenergy plantations for power generation in order to reduce fuel oil imports (Nolan 1985, Tisseverasinghe 1985). Conversely, because of local fuelwood shortages, a massive effort on village woodlot, roadside and railway embankment plantations for fuelwood and charcoal production might be more acceptable to local communities.

iv. In any well-planned national development, the allocation of forest land for particular uses means matching objectives to the resources available and avoiding use of resource capital as a substitute for income. The argument presented in this paper is that, before deciding to modify or transform untouched forest to establish bioenergy plantations, every consideration is given to alternatives. For example areas that are already degraded or under *Imperata* grassland could be adapted to more productive uses such as bioenergy plantations, existing plantation use could be intensified, waste and vacant land (homesteads, roadsides, railway and canal embankments, grounds of factories and government institutions such as schools and provincial offices) could be planted and areas used for more than one purpose where compatible uses can be found (agroforestry offers one set of suitable land management techniques).

v. In the case of protection forests, national parks and nature reserves, land should be allocated specifically for those purposes at the beginning, where this option is still available, and not left as a general reserve of unallocated land which might later be cleared for bioenergy plantations or diverted to other purposes in the future. Bioenergy plantations should be considered for use as buffers around already existing forests, parks and reserves.

vi. Land which is capable of many other uses in addition to bioenergy plantations should be carefully husbanded, as far as is possible, to maintain the widest available range of choices for future generations of people, whose requirements, aspirations and technical skills may be much different to those prevailing at present.

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