REHABILITATION OF DEGRADED LANDS IN INDIA: ECOLOGICAL AND SOCIAL DIMENSIONS

P.S. Ramakrishnan

School of Environmental Sciences, Jawaharlal Nehru University, New Delhi - 110067, India

Received January 1994

RAMAKRISHNAN, P.S. 1994. Rehabilitation of degraded lands in India: ecological and social dimensions. In a developing country such as India, rehabilitation of degraded lands must be closely linked with sustainable community development. Achieving this demands integration of disciplinary approaches by ecologists and sociologists who have traditionally worked separately. This paper considers such a possible synergy using case studies: a multidisciplinary analysis of the shifting agriculture (jhum) system in northeastern India, and an examination of water management as a key factor in successful restoration.

Key words: Rehabilitation - degraded lands - India - shifting agriculture - water management - community participation - sustainable development

RAMAKRISHNAN, P.S. 1994. Pemulihan tanah ternyahgred di India: dimensi ekologi dan sosial. Di sebuah negara sedang membangun seperti India, tentunya pemulihan tanah-tanah ternyahgred berkait rapat dengan pembangunan komuniti secara berkekalan. Ini memerlukan pendekatan disiplin yang berintergasi dari ahli ekologi dan ahli sosiologi yang selama ini telah bekerja secara berasingan. Kertas kerja ini menimbangkan sinergi sedemikian dengan menggunakan kajian-kajian kes: analisis sistem pertanian pindah (jhum) di timur laut India dari pelbagai disiplin, dan kajian pengurusan air sebagai faktor utama dalam pemulihan yang berjaya.

Introduction

Agriculture, forestry and fisheries are traditional activities in the Asian tropics. Increased population has brought considerable pressure on land and water resources. Forest conversion has been accelerated by activities associated with rapid industrialisation, such as mining and energy generation through large hydro-electric projects. Nevertheless, much forest conversion is still due to the extraction of timber for industrial uses and to meet the needs of the rural poor in terms of food, fodder and firewood.

It is in the context of reconciling the needs of the vast majority of the human population with sustainable utilisation of natural resources that the rehabilitation of degraded ecosystems must be viewed. The case study from northeastern India based on a multidisciplinary analysis of the shifting agriculture (jhum) system (Ramakrishnan 1992) indicates the intricate linkages that operate in an ecosystem mosaic comprising agriculture, animal husbandry and other domestic sectors, together with forest ecosystem types derived through various perturbation regimes.

The interplay of ecology, sociology, economics, anthropology and culture is tied together into a meaningful rehabilitation strategy. The other case studies highlight other possible dimensions of rehabilitation in a developing country such as India.

Case study from northeastern India

This case study has two major components: (i) redevelopment of land degraded by clear-cutting forest for industrial purposes and by a shortening of the cycle of shifting agriculture (jhum), and (ii) redevelopment and diversification of the village ecosystem for sustainable economic returns to the farmer. Each component has a variety of ecological and social dimensions and therefore restoration ecology work transcends a variety of disciplinary areas such as agroecosystems, hydrology, soil biology and fertility, tree biology, weed ecology, forest ecology and social, economic and cultural dimensions.

Rehabilitation of land affected by shifting agriculture (jhum) in northeastern India

The increasing agricultural yields of recent years were made possible through industrialisation of agriculture involving heavy subsidies. Though these agroecosystems are efficient in terms of human time and labour, they are highly inefficient in ecological terms. The obvious limitations of such systems as models of development in an energy limited world (Steinhart & Steinhart 1974) has led to a renewed scientific interest in traditional systems of agriculture, as the latter are considered to be models for ecological efficiencies. The forest farmer in the humid tropics has managed his shifting agriculture for centuries with optimum yield on a long term basis, rather than trying to maximise production on short term considerations (Spencer 1966, Ruthenberg 1976, Toky & Ramakrishnan 1981a, Ramakrishnan 1984). It is considered possible to increase production without departing too much from this traditional system.

The jhum cropping pattern

This land use system, as seen in northeastern India, involves slashing the vegetation, burning the dried slash before the onset of the monsoon, raising a mixture of crops on a temporarily nutrient-enriched soil for a year or two, fallowing the plot for regrowth of natural vegetation, and eventually returning to the same plot for another cropping phase after a few years. One jhum cycle is regarded as the time interval between two successive croppings; until a few decades ago this cycle was 20 years or more but is now contracted to five years or less in northeastern India and in many parts of the world (Nye & Greenland 1960) due to increased population pressure and reduced land availability.

Boserup (1986) hypothesised that limited land area eventually leads to settled intensive agriculture, as is the case of Maya tribes in Central America (Lambert

1985). These transitions have also occurred in northeastern India (Gangwar & Ramakrishnan 1987). Shortening of the jhum cycle below five years has often resulted in a fallow system of cropping (FAO/SIDA 1974) where burning is dispensed with. Higher population densities around urban centres where marketing facilities are available often lead to sedentary agriculture. A standard feature of almost all shifting agriculture systems is the practice of mixed cropping, once considered primitive by agronomists and soil scientists (Sanchez & Buol 1976) and now suggested as a means to increase world food production (Andrews & Kasam 1976). Thus, during the cropping phase, the farmer in northeastern India may raise 8-35 crop species on a plot of 2-2.5 ha, with simultaneous sowing and sequential harvesting (Table 1) (Ramakrishnan 1984). The Hanunoo farmer in the Philippines may have up to 40 cultivars at the same time (Conklin 1957).

Table 1. Sequential harvesting of crops on jhum plots under 30-year cycle at lower elevation in Meghalaya

Species	Harvesting time
Setaria	mid July
Zea mays	mid July
Oryza sativa	early September
Lagenaria spp.	early September
Cucumis sativa	early September
Zinziber officianalis	early October
Sesamum indicum	early October
Phaseolus mungo	early October
Cucurbita spp.	early Novemmber
Manihot esculenta	early November
Coloeasia antiquorum	early November
Hibiscus sabdariffa	early December
Ricinus communis	perennial crop

Source: Toky & Ramakrishnan 1981a.

Such an organisation of crop mixture has a number of advantages. It provides good ground cover, preventing nutrient loss through runoff; optimal use is made of available land (Toky & Ramakrishnan 1981b); biomass and nutrients are recycled through crop and weed residues (Mishra & Ramakrishnan 1984, Swamy & Ramakrishnan 1988a); and soil characteristics are improved through surface mulching (Ramakrishnan 1984).

The economic efficiency of the agricultural system is related to a large extent to the length of the agricultural cycle. A comparison of 30-, 10- and 5-year jhum cycles at lower elevations in Meghalaya in northeastern India showed that yield declined with the shortening of the cycle, but that under a 10-year cycle, economic (Toky & Ramakrishnan 1981a) and energy (Table 2) (Toky & Ramakrishnan 1982) efficiencies were optimal.

A variety of regional patterns and social differences occur in the jhum. In northeastern India, the lower altitude jhum system (Toky & Ramakrishnan 1981a) consisting of clear-cutting of the forest followed by total slash burn and subsequent mixed cropping (with emphasis on rice) on unprepared steep slopes, differs from the higher altitude (1500 m) system. The latter (Mishra & Ramakrishnan 1981) involves elaborate preparation of the land into ridges and furrows, partial slash and burn of the sparsely distributed pine trees, and emphasis on tuber (particularly potato) and vegetable crops on the ridges, with the furrows acting as water channels running down the slope.

Table 2. Energy ratios in agricultural systems - jhum, terrace and valley cultivation

	Energy (MJ ha y^{-1})		
Agricultural system	Input	Output	Output/input ratio
Jhum - 30 year cycle	1665	56 766	34.1
Jhum - 10 year cycle	1181	56 601	47.9
Jhum - 5 year cycle	510	23 858	46.7
Terrace	6509	43 602	6-7
	(8003)		(4-5)
Valley - I & II crops	2843	50 596	17.8

Source: Toky & Ramakrishnan 1982.

These modifications reflect the lower nutrient status of the acidic soil of podsolic origin and slower regeneration of the sub-humid montane forest (Mishra & Ramakrishnan 1981, Mishra & Ramakrishnan 1983). Nevertheless, the economic return from the high altitude system may be more than three times greater than that from the low altitude system. Economic return also varies considerably over short distances depending on the crop mixture (Gangwar & Ramakrishnan 1987); manipulation of the crop mixture, therefore, offers possibilities of improved returns to the farmer.

Weeds, which normally are considered to be undesirable and to adversely affect crop yield in agroecosystems (Seavoy 1973), often play a useful role in traditional agriculture. The traditional forest farmer of northeastern India leaves about 20% of the weed biomass *in situ*. Under such husbandry, the crop yield is unaffected and indeed the weed ground cover helps to conserve soil nutrients. Weed biomass pulled out but retained in the agroecosystem contributes to nutrient cycling (Swamy & Ramakrishnan 1988a). Weeds also create an unfavourable environment for biological pest invasions (Altierie 1983). This useful role of weeds in traditional agriculture has potential application to tropical agriculture (Gleissman *et al.* 1981, Swamy & Ramakrishnan 1988a).

Other land use options

Valley cultivation

Valley cultivation offers many advantages over jhum. Soil and nutrient losses are heavy from slopes under jhum, but valley cultivation is a nutrient sink. However, jhum provides higher monetary returns because of greater crop diversity and the higher returns from potato compared with rice. Hilly terrain also offers restricted opportunities for valley cultivation. However, a distinct advantage of valley systems is that the land re-use factor is 1 whereas for jhum it is 0.1 or 0.2, i.e., the land is cropped only once or twice in 10 years. The energy output/input per hectare per year for both systems are similar to that discussed by Leach (1976) for pre-industrial farming, although jhum compares unfavourably due to the low re-use factor.

The greater returns provided by sedentary valley cultivation compared with jhum is illustrated by agricultural practices at lower elevations of Meghalaya. Here the Nepalis and the Mikirs take only one crop during the monsoon, under valley cultivation, whereas the more laborious jhum-practising Garos take two, one during the monsoon and another during the winter (Maikhuri & Ramakrishnan 1990). However, the land use system of the Garos is less efficient than that of the Nepalis; the net return through the latter's valley cultivation with one annual cycle is comparable with that of the 20-year jhum cycle of the Garos. The single annual crop cycle of the Nepalis may be due to their preoccupation with a well developed dairy cattle husbandry.

Unlike most of the other tribal communities of northeastern India, the Aptanis have a highly evolved sedentary agriculture in the form of wet rice cultivation in their extensive valley lands. Irrigation farming such as wet cultivation of rice requires cooperation of several farmers and communal work to maintain the water delivery system (Ruthenberg 1976). The Aptanis have optimised water use in their fields through a system of cooperative management of water delivery under the supervision of the village headman. In the absence of a disciplined schedule of water distribution among the beneficiaries, economic returns could decline drastically.

Aptanis make best use of their irrigated lands by planting early and late ripening varieties of rice. The early ripening variety is sown further away from the village to minimise disturbance by animals. Closer to the village, where irrigation facilities are better, the late ripening variety is preferred. Rice is supplemented by millet (*Eleusine coracana*), cultivated on the elevated bunds between the rice plots, and also by pisciculture, made possible by the assured water supply. The production of about 50 kg of fish per hectare provides additional income of about Rs. 1000, equivalent to the cost of about 450-500 kg of rice. This compares favourably with similar pisciculture systems from Java and Madagascar (Hickling 1961). The Aptanis obtain high energy output in crop yield with very little organic manure use, and with human labour as the major input. The efficiency of the system expressed as output/input ratio is very high (60-78), compared to a value of about nine for traditional Indian agricultural systems (Mitchell 1979) and for traditional rice cultivation elsewhere in the Philippines (Nguu & Palis 1977). Such a high energy efficiency with a reasonable monetary efficiency of about three, makes the rice system of the Aptanis an effective model of traditional agriculture. The high energy efficiency obtained here is even greater than that recorded for shifting agriculture in northeastern India (Mishra & Ramakrishnan 1981, Toky & Ramakrishnan 1982) and elsewhere (Rappaport 1971, Steinhart & Steinhart 1974).

With 27-35 MJ of energy output per labour hour, the Aptani valley system compares favourably with similar systems of China (Dazhong & Pimental 1984) and the even more modern agriculture of industrialised societies (Leach 1976).

Home garden

The home garden of the Mikirs (Maikhuri & Ramakrishnan 1990) is a complex production system (Mitchell 1979), with an effective organisation of crop mixture and use of space through stratification of the plant community. It is unsurprising to find three to five-fold economic returns from a home garden system compared with jhum. This important land use concept could provide cash income to the tribal communities, and reduce their dependence on jhum.

Terracing

Sedentary terrace farming on the hill slopes has been suggested as an alternative to jhum, but has been repeatedly rejected by the farmer for valid reasons: (i) terracing is expensive to establish and maintain, both in terms of labour and monetary input, particularly under high rainfall conditions, (ii) heavy inputs of costly and difficult to obtain inorganic fertilisers are required, (iii) weed potential is intensified on the terraces as much as or even more than under a short jhum cycle of 4-5 years (it may be mentioned here that weed potential increases drastically with the shortening of the jhum cycle), and (iv) even if runoff losses are checked though terracing, leaching of minerals through percolating water is accelerated, because of the loose and porous soil.

Recently the Indian Council of Agricultural Research (ICAR) suggested a three tier system for a given slope as an alternative to jhum (Borthakur *et al.* 1978). Under this system the upper part of the slope remains under forest cover, with plantation/ horticultural crops on the mid-portion and terraces on the lower part of the slope. Apart from problems similar to those described for terrace cultivation, the major drawback of the ICAR model is that such a rigid system may conflict with the societal organisation of the tribals. For example, the independence of the family unit would be adversely affected. In any case, the ICAR model has not yet made a significant impact.

Landuse redevelopment

There is scope for redevelopment of shifting agriculture whereby the distortions in terms of economic yield (Ruthenberg 1976, Ramakrishnan 1984) and land degradation (Ramakrishnan 1985a) brought about by shortened cycles can be corrected. Agricultural systems must be both sustainable and independent of massive inputs of fossil fuel derivatives (Ewel 1986). Thus, the following ecological attributes must be incorporated into the design of agroecosystems for the humid tropics: (i) low requirements for nitrogen and phosphorous as external subsidies, (ii) efficient use of available resources, (iii) protection from biological invasion, and (iv) low risk. These features can be obtained by constructing mixed-species communities that imitate successional vegetation (Hart 1980).

Agroforestry, or the deliberate association of trees, shrubs, crops and livestock, holds great promise for the development of sustainable land use systems. Some of the earliest recognised forms of agroforestry involved modification of the farming practices of shifting cultivators to include the planting of tree seedlings with food crops. As the tree canopy develops and begins to shade the annual crops, the farmers move to another area for cropping. Using this system of "taungya" large areas of teak plantations have been established in Indonesia and Nigeria (Winterbottom & Hazlewood 1987).

In recent years the International Institute for Tropical Agriculture (IITA) in Nigeria has experimented with the hedgerow technique and has developed a new system of alley cropping (Kang & Duguma 1984). Here *Leucaena*, a fuel and fodder tree, intercropped with maize, can fix up to 160 kg per hectare per year of nitrogen, or enough to sustain maize yields at a level of 2 t ha^{-1} y^{-1}. During one cropping phase the agricultural systems in northeastern India may lose about 600 kg ha^{-1} of nitrogen; not more than one half of this loss is recovered during the natural fallow period of five years (Mishra & Ramakrishnan 1984). An accelerated and directed succession through the introduction of a variety of legumes and non-leguminous alder (*Alnus nepalensis*) during the cropping and fallow phase could restore the soil fertility over a five-year cycle period (Ramakrishnan 1987). Many other early successional trees that are fast growing with a high leaf turnover, and even fruit trees of economic value, could be useful; they could also provide a wind-break around plots to prevent ash blow-off (Ramakrishnan 1987).

Other strategies could be based on alternate land use development. Some possibilities are settled terrace cultivation as trialled in Bangladesh and India (FAO 1978), intensified valley cultivation and a shift to plantation/horticultural crops. Terrace cultivation in these areas may be of limited value, because heavy leaching of nutrients occurs even if runoff losses are checked. Studies from Sarawak in Malaysia suggest that cash cropping could eventually replace shifting agriculture (Chin 1982).

The forest village scheme introduced by the Forest Industries Organisation (FIO) of Thailand in 1967 emphasises the development of a home garden and the establishment and maintenance of forest plantations (Broonkird *et al.* 1984). In these plantations, the raising of agricultural crops is encouraged for the first few years. This scheme is integrated with health and education programmes and crop and animal husbandry extension, and is proving to be a successful alternative to shifting agriculture.

Experience in India and elsewhere suggests that rubber plantations established on a cooperative basis could ensure people's participation (Ramakrishnan 1985b). While short term strategies may emphasise redevelopment of shifting agriculture itself, long-term strategies may consider alternative land use systems with the participation of the people involved. The objective here should be to relieve the pressure on land for jhum so that a 10-year cycle can be sustained. This cycle has been found to be economically and ecologically efficient (Ramakrishnan 1984).

Integrated animal husbandry

Improved and better managed animal husbandry, where it is ecologically viable and a part of traditional practice, could meet protein needs as well as providing additional income through export. There is also scope for development of improved breeds.

Swine husbandry is an integral part of the jhum system in northeastern India (Mishra & Ramakrishnan 1982) and is also part of this landuse in many other parts of the world. Thus, the Tsembaga farmer of Papua New Guinea raises pigs to be eaten as part of social and religious ritual (Rappaport 1971). In fact, the tribal farmer of northeastern India consumes pork not only as a part of his normal diet but also makes a feast of it during celebrations related to jhum procedures. Again, the main reason why swine husbandry is part of the jhum system is its inexpensive maintenance costs.

This animal husbandry practice is based on efficient recycling of resources with a reasonable level of energy efficiency, the principle on which the operation of the jhum system itself is anchored. A study of the animal husbandry sub-system of a Khasi village ecosystem of 20 members (Mishra & Ramakrishnan 1982), found that the majority of the energy input was accounted for by animal feed, of which crops accounted for about 4.9%, while the rest comprised crop residues plus grazing, which are essentially free commodities. Animal husbandry is an important source of protein for the villagers.

Rural technology

Appropriate technology may be introduced to the village units, either to relieve drudgery through better implements for shifting agriculture, or to improve efficiency of fuel wood use through energy efficient stoves, or to generate energy through mini- or micro-hydro projects or unconventional sources such as solar power.

Artisan skills such as leather technology, black-smithy or wood and bamboo works could also be developed. For these purposes, the resource base available to rural communities needs to be conserved. The rapid rate of extraction of bamboo for industrial purposes without replenishment (Rao & Ramakrishnan 1987) is a case in point. The strengthening of agroforestry and social forestry programmes (Ramakrishnan 1987) based upon the value systems of the local communities is integral to the conservation of the resource base.

Philosophy for rural development

Specially designed packages have to be developed for each cluster of villages, taking account of micro-climatic conditions, socio-economic levels and the socio-cultural background of the people. The aspirations of tribal people are unique (Ramakrishnan 1984, 1985a) because of their close integration with the environment. This dependence on nature is reflected in the undisturbed "sacred forest" which was often maintained as part of the village system. These characteristics should be adequately protected when planning for development. Scientists, planners and administrators have often tried to impose development plans that they consider are good for people in a region, without trying to understand the processes that operate in traditional ecological systems. The strategy for development should be one with which the local people can identify. Such a planning philosophy would take care of the traditional value systems, and, therefore, would not only find ready acceptance by the tribal societies but would also ensure their participation in the developmental process.

The village headman is the key person in each tribal settlement. Village level institutions linked with the District Council infrastructure could provide the necessary institutional framework for development planning. The planning approach should incorporate a review period so that appropriate adjustments may be made based on experience.

Forest ecosystem redevelopment in the humid tropics

Natural disturbances of varying magnitudes are common in the forests of the humid tropics. These may be due to tree fall, which often occur as localised events in natural forests, clearing of a forest for shifting cultivation, or large scale timber extraction. As long as brief epochs of high mortality are followed by relatively long quiescent recovery periods, the forested ecosystem remains stable. However, severe traumatic events of high intensity and greater frequency covering larger areas cause damage from which the forest does not readily recover. In this account, the problems of redevelopment of forested ecosystems in the humid tropics is considered with particular reference to the case study from northeastern India.

Level of disturbance and secondary succession

The effects of small-scale disturbances on gap-phase regeneration and restoration of ecosystem properties is known largely from the work on tropical rainforests of Malaysia (Whitmore 1978, 1983). Seedlings already present in the undergrowth respond opportunistically to small canopy gaps. In a larger gap, where the microclimate may undergo a marked change due to an increase in insolation, pioneer species may regenerate rapidly from the soil seed bank (Ashton 1978). We have shown that germination of early successional trees is accelerated under high light regimes for a variety of species in northeastern India (Shukla & Ramakrishnan 1982). However, perhaps because of competition from fast-growing pioneers (Lagenhelim *et al.* 1984) or because of insect attack as in Dipterocarps in Malaysia (Whitmore 1984), shade-tolerant undergrowth seedlings fail to survive. These processes merit further attention as there are implications for the management of tropical forests and restoration of large gaps.

During conversion of a forest to cultivable land, not only is the original vegetation destroyed, but the site is subject to continuing perturbations due to fire, introduction of crop species, weeding, hoeing and other disturbances during harvesting (Toky & Ramakrishnan 1983). These result in a progressive reduction in species diversity that reverses gradually as the secondary succession develops. The pattern of secondary succession and the rapidity with which a forest community develops depends upon the degree of destruction of the prefarming vegetation and of its propagules in the soil. During the first few years, weed species predominate.

Thus, under shorter jhum cycles *Eupatorium odoratum, Mikania micrantha* or *Imperata cylindrica* predominate at lower elevations in northeastern India (Toky & Ramakrishnan 1983) while *Eupatorium adenophorum, Imperata cylindrica* or *Pteridium aquilinum* predominate at higher elevations. Under continuous imposition of short jhum cycles of 4 to 5 years, succession is arrested at the weed stage (Saxena & Ramakrishnan 1984a). If the cycle is longer, the vegetation at lower elevations in northeastern India changes rapidly from weeds to bamboo (*Dendrocalamus hamiltonii*) and other shade intolerant trees, while at higher elevations it converts to pine forest (Ramakrishnan & Das 1983). Later in the succession after about 50 years, many shade-tolerant trees such as *Artocarpus chaplasha* appear at lower elevations (Singh & Ramakrishnan 1982) or a mixed broad-leaved forest of *Quercus* spp. and *Castanopsis* sp. develops at higher elevations (Boojh & Ramakrishnan 1983a).

Under shorter jhum cycles of 4 to 6 years with more frequent burning, early succession follows an "initial floristic composition model", whereas a "relay floristic composition model" operates under longer cycles (10 years or more) (Saxena & Ramakrishnan 1984a). Such differences in vegetation development patterns are to be expected because of the variation in vegetation structure at the pre-burn stages under long and short jhum cycles. The high reproductive potential of the early successional weeds due to the heavy production of propagules during the fallow phase coupled with a low intensity burn accounts for a high weed population under shorter cycles, compared with longer ones of 10 years or more. The viable soil seed population of weeds under shorter cycles is therefore highly exaggerated (Figure 1).

Strategies of colonisers and ecosystem redevelopment

In many rainforests, mats of climbers such as *Merremia* in the Solomon Islands and Malaysia (Whitmore 1991) and *Mikania micrantha* in northeastern India (Swamy & Ramakrishnan 1987a) are serious impediments. Rhizomatous weeds such as *Imperata cylindrica* are extensive in the region (Eussen & Wirjahardja 1973, Kushwaha *et al.* 1983). *Eupatorium* spp. from Latin America are also extensive. If tree seed sources are not available nearby and if seedling establishment is hampered by dense weed communities, forest regeneration through natural processes is arrested. In extreme cases the landscape may be totally denuded because of very thin and nutrient poor soils and exceptionally high rainfall, as at Cherrapunji in northeastern India (Khiewtam 1986, Ramakrishnan & Ram 1988). Here, even if

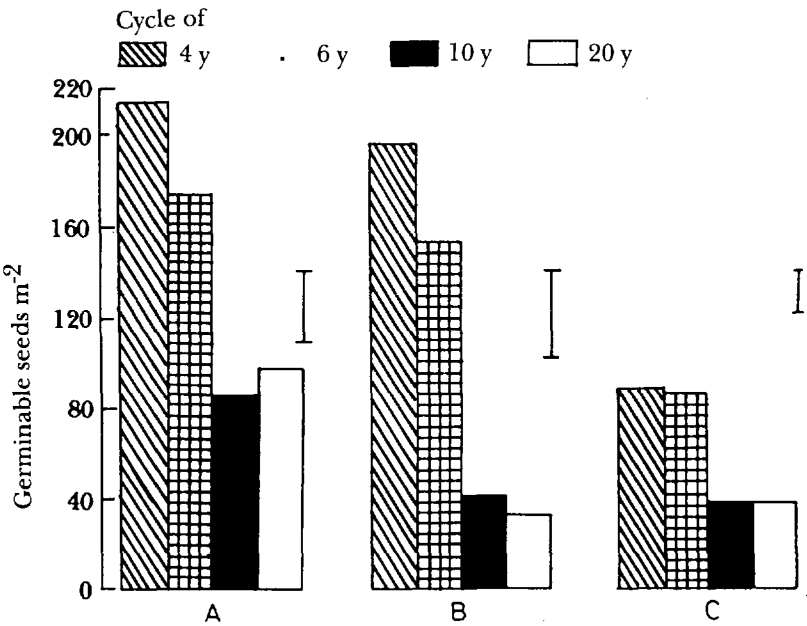

Figure 1. Population of germinable weed seeds under different cycles

seed sources of large trees are present, as in the ecotone of sacred groves with degraded sites (Boojh & Ramakrishnan 1983a, Khiewtam 1986), these seeds fail to establish.

Revegetation of the arrested weed stage and of the denuded landscape must be achieved through manipulation of plant growth strategies, and the use of successional concepts. This is the basis for the following discussion of the case study in northeastern India, which has wider management implications for restoration programmes in the region.

Early successional communities in the northeast include a variety of herbaceous weeds, both native such as *Imperata cylindrica* and *Thysanolaena maxima*, and exotics such as *Eupatorium* spp. and *Mikania micrantha*. These and many others broadly have three strategies for reproduction: (a) predominantly clonal reproduction through extensive rhizomes in the former two, (b) predominantly seed reproduction as in *Eupatorium*, and (ç) a combination of clonal and seed reproduction as in *Mikania micrantha* (Saxena & Ramakrishnan 1982,1983a,b, Swamy & Ramakrishnan 1987a). Exotics have a high seed production, and establish through seedlings (Kushwaha *et al.* 1981, Ramakrishnan & Mishra 1981). Fire often plays a regulating role, e.g.in *Imperata cylindrica* and *Mikania micrantha* (Swamy & Ramakrishnan 1988b). These reproductive strategies are significant in slash and burn systems. R-strategists are more successful under shorter cycles of frequent, mild burns; thus selection of species for restoration of damaged sites has to be based on the most suitable strategy for the success of the early colonisers.

Equally significant in a restoration programme is the complimentarity of early colonisers, and their organisation in space and time. In an early successional environment after shifting cultivation on a hill slope, the soil is nutritionally heterogeneous. Nitrogen in particular is highly labile and therefore its availability in the early stages is uncertain (Ramakrishnan & Saxena 1984, Saxena & Ramakrishnan 1986). C3 species such as exotic *Eupatorium edoratum* and *Mikania micrantha* which have a low nutrient use efficiency (Figure 2) occupy nutrient-rich microsites; C4 natives such as *Imperata cylindrica* and *Thysanlaena maxima* which have a higher nutrient use efficiency largely occur in nutrient-poor microsites (Saxena & Ramakrishnan 1984b). Continuous imposition of agricultural cycles enable a larger biomass to be achieved by C3 exotics through greater light interception and more efficient allocation of resources to the shoot system (Saxena & Ramakrishnan 1983a). Long fallow periods would on the other hand impoverish the soil seed bank, and intense burns would further destroy the seed bank, whereas soil insulated below ground rhizomes of C4 grasses would better survive intense burning.

The consequences at the ecosystem level of biological invasion are considered in detail by Ramakrishnan and Vitousek (1989). Here the occurrence of a species such as *Mikania micrantha* is significant for restoration ecology. Where this is an important component in the community during the first four years of fallow regrowth, potassium is accumulated rapidly; this species enrichment quotient was the highest recorded (Table 3). The conservation of this labile element is critical at this stage of fallow regrowth and recovery of soil fertility (Ramakrishnan & Toky 1981).

Tree growth strategies, architecture, succession and forest ecosystem rehabilitation

Redevelopment of forest ecosystems must involve the introduction of tree species into the plant community after the initial phase of herbaceous colonisers.

Rehabilitation of forested ecosystems based on successional concepts and architectural compatibility in species mixtures represents a new perspective in ecosystem redevelopment, indicating possibilities for faster regeneration of forests.

The ultimate architectural form of the tree is based on the rate of growth of the leader axis versus lateral branches, the bud dynamics and the pattern of branch production, the birth and death rates of leaves, and the final display of the branches and leaves on the tree trunk. These characteristics are related to environmental conditions, as well as being a consequence of natural selection and therefore part of an evolutionary process which is species-specific. Light is obviously an important factor in shoot architecture, and soil nutrient and water availability are important in determining root architecture. Thus, there is a need for a greater appreciation of the physiological ecology of regeneration for better management of rainforests (Bazzaz 1991).

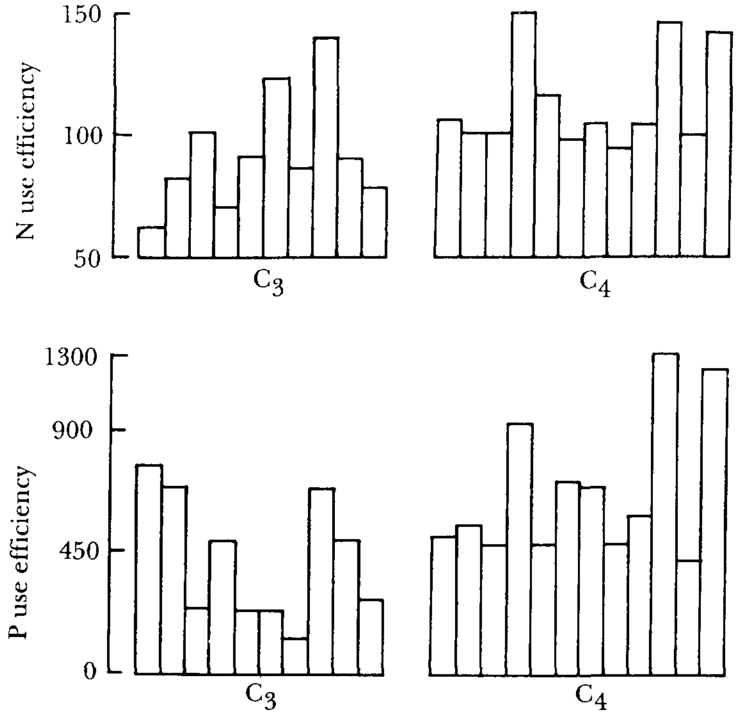

Figure 2. Nutrient use efficiency of colonisers

Table 3. Enrichment quotients (elements held in vegetation/annual element uptake) for *Mikania micrantha* and the total vegetation in successional fallows developed after shifting agriculture in northeast India

Fallow age (years)	N	P	K	Ca	Mg
0-1	0.85 (1.14)	0.97 (1.25)	1.00 (1.32)	0.85 (1.08)	0.88 (1.17)
1-2	1.03 (1.42)	1.12 (1.74)	1.18 (1.60)	1.03 (1.33)	0.98 (1.29)
2-4	1.19 (2.12)	1.30 (2.67)	1.61 (2.74)	1.22 (1.90)	1.07 (2.41)
4-8	1.85 (2.63)	1.94 (5.62)	2.55 (4.01)	2.44 (2.64)	1.46 (3.20)
8-12	1.93 (3.08)	2.19 (4.64)	2.81 (6.15)	2.47 (3.58)	1.52 (3.34)

Values in parentheses are for total vegetation.
Source: Swamy & Ramakrishnan 1987b.

An important characteristic of early successional species is the rapid growth of the leader axis. This facilitates the exploitation of the high light environment, in contrast to late successional species which have slower growth. Faster growth is partly because of a faster rate and a greater duration of growth activity (Boojh & Ramakrishnan 1982a, Shukla & Ramakrishnan 1986). Another attribute of early successionals is the production of relatively more branches and leaves, unlike late successionals which have restricted leaf and branch production. An excurrent (narrow) crown form is achieved by early successionals partly through stronger correlative growth inhibition with apical control over the growth of the branches beneath, and partly through rapid extension of the first order branches at the expense of second order branches (Shukla & Ramakrishnan 1986). In contrast, the contribution of the first order branch system for crown development compared with subsequent orders of branches is lesser for late successionals and consequently a decurrent (broad) crown form with more peripherally placed leaves is obtained.

With a large leaf population per tree due to faster production and turnover rates, the early successional species have a larger proportion of younger leaves with a relatively short life span (Boojh & Ramakrishnan 1982b, Shukla & Ramakrishnan 1984a). In contrast, late successional trees have a larger proportion of older leaves, a slower turnover rate and a longer leaf life span. It is concluded that the rapid growth of early successional trees is more related to their ability for unrestricted leaf production than to efficient energy conversion per unit leaf area.

Biomass allocation strategies of the early versus late successional trees are also geared to the exploitative strategy of the former and the conservative strategy of the latter. Early successional trees allocate more to the shoot components than to the root components compared to late successional trees (Shukla & Ramakrishnan 1984b) which enables early successionals to achieve faster growth for better exposure of the canopy. Further, the early successionals allocate more to the bole compared to the branches, unlike late successionals. The superficially placed root system of early successional trees helps in exploiting the nutrient rich surface soil layers of the gap environment whereas the deeply and more uniformly distributed root systems of late successional trees exploit more deeply distributed nutrients in the soil profile.

Complementarity of species may be ensured by the choice of appropriate architectural attributes. One could have not only a well-designed mixed plantation programme (Figure 3) but succession could be condensed by varying the time of introduction of the species into the mixture. Thus species such as *Anthocephalus cadamba* or *Duabanga sonneratiodes* could be followed by mid-successionals like *Dillenia indica*, with *Artocarpus chaplasha* being introduced later (Shukla & Ramakrishnan 1986). The architectural attributes of early successionals are appropriate for agroforestry systems, as the loose organisation of the leaves permit sufficient light penetration to the ground level, and the fast leaf turnover enables efficient nutrient cycling within the system. With generally fast growth rates for these and with even faster rates for selected ecotypes of species such as *Schima* *wallichii* (Boojh & Ramakrishnan 1982c, 1983b) this category of species could meet fodder, fuelwood and timber needs.

Nutrient cycling in the forest fallows is determined by some key species during secondary succession (Ramakrishnan 1989). Earthworms in the surface soil help in concentrating nutrients through worm casts (Bhadauria & Ramakrishnan 1989,1991). Bamboos play a key role in nutrient conservation. *Dendrocalamus hamiltonii*, in particular, concentrates potassium (Ramakrishnan & Toky 1981). The role of *Mikania micrantha* under shorter jhum cycles of 4 - 5 years is performed by this bamboo under longer jhum cycles of 10-30 years, since it dominates at this stage of fallow regrowth. Other bamboos such as *Bambusa tulda, B. khasiana,* and *Neohouzoa dulloa* are also important for conserving nitrogen, phosphorus and potassium (Rao & Ramakrishnan 1989). Nepalese alder (*Alnus nepalensis*) is another species which improves nitrogen status of the soil. Such species are important in any rehabilitation work.

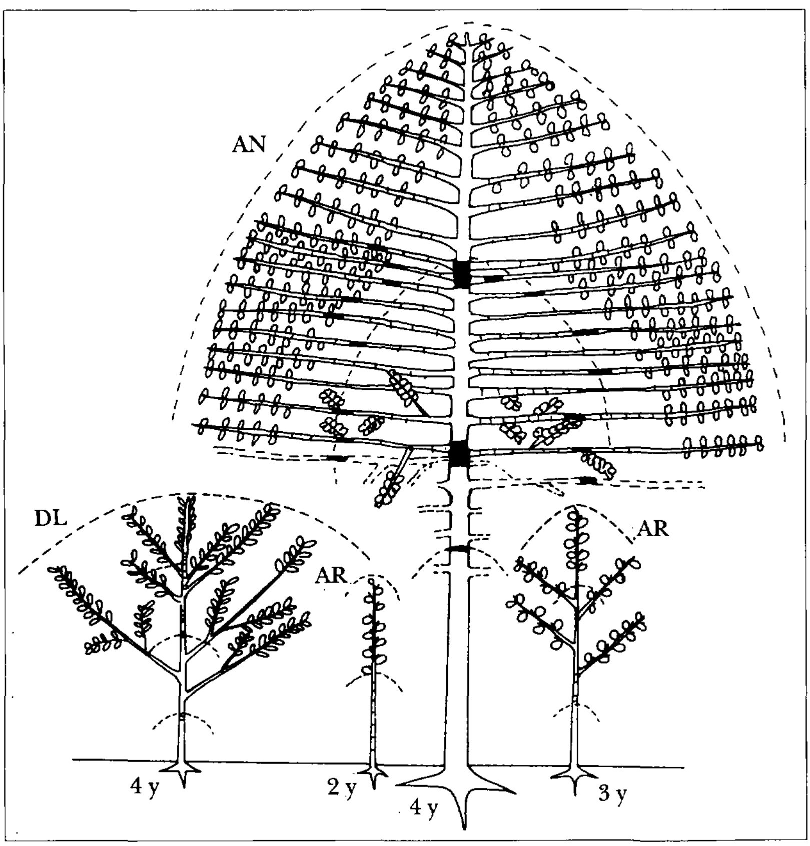

Figure 3. Model of a mixed plantation with complementarity of species governed by architectural attributes

Buffer zone restoration

In a synthesis of a number of studies of buffer zone restoration, Sarabhai *et al.* (1990) emphasised the need to incorporate sustainable development strategies for the human residents of the zone, taking into consideration their dependence upon the forest resource. The two case studies on Hirogolgadh and Ranthambore National Parks highlight the issues and problems related to conflict between the governmental agencies and the local communities in buffer zone management and restoration. Some restoration activities have been initiated in buffer zones through the efforts of non-governmental voluntary agencies, and these activities are based upon local perceptions of environment and development. The case study from West Bengal illustrates how local support can be ensured for restoration work if the governmental agencies can perceive the issues from the point of view of the local community.

West Bengal is one state in India where community woodlots under the social forestry programme have achieved some success (Agarwal & Narain 1985). This was due to the interest generated amongst the rural communities, and their consequent active involvement in the programme. It is this context of cooperation between villagers and the Forest Department of West Bengal that another experiment in forest protection and regeneration has to be viewed (Malhotra & Poffenberger 1989). In 1972, a sal (*Shorea robusta*) regeneration project was initiated by the Forest Department in the Arabari area in southwest Bengal. Sal is an important timber tree species and is highly productive and economically attractive compared to other species in plantation. The Forest Department had two options - either to police the forest reserve, or to involve the villagers in the management programme. The latter option demands that the villagers' needs have to be adequately met; one solution would have been to employ the villagers as forest guardians. This, however, has a limitation - forest protection would lapse when the monetary incentive was withdrawn. The Forest Department adopted another approach. The villagers were granted exclusive rights to all minor forest products, a 25% share of the extracted timber, and supplemental employment programmes. The people in return provided free labour and guaranteed protection of over 600 ha of Sal forests. The degraded forests regenerated very rapidly.

The message from Arabari spread. During the last eight years, more than 1250 villages have formed their own Forest Protection Committees (FPC) covering about 152 000 ha of degraded forests. Since this protection is achieved through community effort, the cost of restoration of the degraded forest ecosystem was minimal. Village communities are allowed to collect twigs for firewood, dried leaves of specific tree species for tableware (plate making) and for rolling bidis (a local cigarette) and medicinal plants. In mutually identified sites, they are even permitted to practice agriculture to a limited extent. The approach for forest management is truly an integrated one and provides income up to about Rs. 3500 per family based on access to one hectare of forest per family.

Water: a precious resource for restoration

Restoration activity in India is often constrained by lack of water outside the monsoon season. This is further exacerbated in a hilly terrain. Uneven distribution of rainfall interacting with excessive land degradation has often aggravated the water shortage. Poverty leading to depletion of natural resources and land degradation is a vicious cycle.

The Sukhomajri model

The village of Sukhomajri is located near Chandigarh in northwestern India, in the Shiwalik ranges which are foothills of the Himalaya. Prior to the restoration work (Grewal *et al.* 1990) the inhabitants of this village experienced frequent crop failures due to erratic rainfall and soil erosion; this compelled the farmers to shift to animal husbandry with emphasis on goats and sheep. The even greater fodder demands lead to further degradation of the forests, already depleted by fuelwood extraction. Severe land erosion also resulted in sediment inflow to the nearby Sukhna Lake at the rate of 141 t ha^{-1} y^{-1} (Bansal & Grewal 1986).

The Hill Resource Management Society (HRMS) constituted in the village with support from the Central Soil and Water Conservation Research and Training Institute Research Centre at Chandigarh identified water as the limiting resource.

Three earthen dams were constructed during 1976-1980, and another in 1985. Each hectare of forested land provides supplemental irrigation for two hectares of farmland, so that 32 ha of cropland are now irrigated (Grewal *et al.* 1990). With improved agricultural technology, wheat yield more than doubled from 2 to 4.4 t ha^{-1} y^{-1}. Total food grain production increased from 45 t in 1975 to 182 t in 1986; the fodder yield increased from 73 t to 292 t over the same period. With good forest and grass cover, soil erosion was checked. Milk production in the village increased by 750 litres per day due to an increase in stall fed buffaloes and a drastic decline in the goat population (Table 4). In just five years, annual household income increased by an estimated Rs. 2000 to Rs.3000.

Table 4. Impact of Sukhomajri project on cattle population in the village

Animal	Population			
	1976	1980	1985	1986
Goat	144	54	8	8
Cow	14	12	6	6
Buffalo	129	167	228	291
Bullock	79	88	96	96
Total	366	321	338	401

Source: Grewal *et al.* 1990.

The Sukhomajri model had the following salient features: (i) excess monsoon rainwater was harvested through earthen dams, (ii) this water was distributed through underground pipelines through gravity flow to farmlands, (iii) appropriate soil and water conservation measures such as the planting of trees and grass were applied to the watershed, (iv) agricultural and animal husbandry were improved through the development of farm forestry, horticulture and reservoir fisheries, and (v) local support was ensured by participation in organised societies for equitable water distribution and restoration work in the watershed.

The success of this experiment is largely due to the village level institution (HRMS) which consisted of one member from each household in the village. Its mandate was to provide a forum to sort out problems related to implementation of various tasks, ensure fair distribution of water, fuelwood and fodder within the village and oversee discipline within the community.

The Sukhomajri model has been replicated to restore degraded ecosystems in many villages in the region (Grewal *et al.* 1990). One example is Nada village, near Chandigarh. This village had four different communities, with the more powerful Rajputs at one extreme and the Harijans at the other. Separate dams had to be built for each community. The dam meant for the latter was designed in such as way that the water would only reach the Harijan community. However, another problem remained. The Harijans with little private land of their own had to depend on the village common and forest land for fodder for cattle, and for grass for a variety of other activities such as rope making and thatching the house. As the more resourceful Rajputs operated the common land through a society, they laid claim to the produce from the village commons. Thus there are social problems to be resolved while attempting restoration of degraded rural systems (Agarwal & Narain 1989).

The Himalayan experiment: preliminary results

Restoration of degraded land in the central Himalayan Kumaon region is a major task and is critical for the economy of the local people. Restoring forest and grass cover on a denuded landscape, sustainable use of the biomass for timber, fuelwood and fodder, and a redeveloped agroecosystem require the support and participation of the people.

Water management was again identified as the key issue if restoration work is to be successful. Where the human and attendant cattle and goat populations are very large and the natural resource base is extremely limited, the human aspects of restoration cannot be ignored. Potable water is not adequately available for many hill communities because of the drying up of streams and hill springs as a consequence of extensive deforestation. Water harvesting could act as a remote control for hill slope restoration and to ensure people's involvement.

Rain water harvesting tanks were constructed at a number of sites right across the Himalaya. The objective was to trap runoff water from the hill slopes and to store it in cheaply constructed tanks dug into the ground and lined with high density PVC sheets. Though other governmental and non-governmental organisations had earlier attempted to prove the value of water harvesting in experimental plots under their control, no attempts had been made within the village boundary in the farmers' plots or on the village common land, on a participatory research/ development basis. This was attempted by the present author as an initiative right across the Himalaya, in collaboration with the Scientist of the G.B. Pant Institute of Himalayan Environment and Development, and with support from the Department of Science and Technology, Government of India.

By harvesting runoff rain water during the monsoon and by diverting water from seepage it was possible to generate over 30 m^3 per day of water throughout the year. Total investment in the first year was about Rs. 400 per m^3 of storage capacity generated (comprising about Rs.130 as capital input and Rs. 270 as wages paid to the local community for labour). With negligible maintenance costs in subsequent years, the technology is cheap indeed (Kothyari *et al.* 1991).

The series of water harvesting tanks are linked with a variety of rehabilitation activities. In the Kumaon Himalaya, one project is associated with a mixed forestry programme. The local tree species were categorised as early, middle or late successional trees. A few economically important tree species were identified. About 20 species thus identified were organised into mixtures of different densities and proportions. The objective was to use tree growth form and architecture (Ramakrishnan *et al.* 1982, Ramakrishnan 1986) for their complementarity in a quick forest restoration programme. Preliminary results obtained through this study have been very encouraging. Apart from successful afforestation possibilities, protection of the site from uncontrolled grazing and application of surface irrigation from the tanks during dry spells have resulted in a 10-fold increase (0.3 to 3.3 t ha^{-1}) in yield of palatable grasses during a two-year period.

In another rehabilitation study in the Kapkot region of Kumaon Himalaya, the biological/ecological component in terms of appropriate species for restoration and the role they have in ecosystem level processes are adequately integrated with its social dimensions. Four species of bamboo, *Thamnocalamus apathiflorus, T. falconeri, T. jaunsarensis* and *Chminobamboosa falcata* (locally known as ringal bamboo), were identified to be of socio-economic value to the local community. Ringal bamboo was in very short supply, leading to conflict amongst the villagers. Working in cooperation with a local non-governmental voluntary group we were able to demonstrate a very high establishment rate for these species. The response from the local people was tremendous. In a short period over a hundred local villagers were involved in our restoration work.

These bamboos were considered in pure and mixed stands with other broad-leaved species for social forestry and plantation forestry in private land and village common land. This effort was further extended towards developing agroforestry systems. In all of these, the work was based on participatory research and development. An important focus of the ecological research is bamboo biology and the role of bamboo on soil fertility maintenance and nutrient cycling processes. The research effort is now diversified towards understanding traditional agroforestry systems in this hill region, and to redevelop these. Again, water is identified as a limiting factor. Therefore, rainwater harvesting technology was introduced into the area. About 10 ha of land was already restored in one year through a participatory revegetation strategy. Sustainable utilisation of biomass by the community and simultaneous redevelopment of the agroecosystem have ensured local participation.

Elsewhere in the Garhwal Himalaya, water management through rainwater harvesting tanks is linked with hill agroecosystem development. In the Sikkim Himalaya, it is linked with a whole watershed management project. In Nagaland, in the northeastern hill region, it is linked to the redevelopment of shifting agriculture (jhum).

Conclusion

Ecologists and social scientists have traditionally worked in isolation on similar or related problems but using different paradigms. Rehabilitation of degraded systems will require integration of a variety of these disciplines in a complementary manner. This has been shown through the case studies discussed in this paper. The guiding principles of such an ecologically sustainable resource development and management are listed in Table 5.

Table 5. The guiding principles of ecologically sustainable resource management

- Intergenerational equity: providing for today while retaining resources and options for tomorrow.
- Conservation of cultural and biological diversity and ecological integrity.
- Constant natural capital and "sustainable income".
- Anticipatory and precautionary policy approach to resource use, erring on the side of caution.
- Social equity: resource use in a manner that contributes to equity and social justice, while avoiding social disruptions.
- Limit on natural resource use within the capacity of the environment to supply renewable resources and to assimilate wastes.
- Qualitative rather than quantitative development of human well-being.
- Pricing of environmental values of natural resources to cover full environmental and social costs.
- Global rather than regional or national perspective on environmental issues.
- Efficiency of resource use by all societies.
- Strong community participation in policy and practice in the process of transition to an ecologically sustainable society.

Source: from Hare *et al.* 1990.

The currently evolving ISBI (International Sustainable Biosphere Initiative) aptly stresses this linkage between ecological and social sciences (Huntley *et al.* 1991). In this scheme of things, the linkages between human values and beliefs related to resource use and ecosystem degradation are critical. Only through such as integration can people's participation be ensured, and only through such an integration can sustainable development be achieved.

References

AGARWAL, A. & NARAIN, S. 1985. *The State of India's Environment 1984-85.* Centre for Science and Environment, New Delhi.

AGARWAL, A. & NARAIN, S. 1989. *Towards Green Villages.* Centre for Science and Environment, New Delhi. 52 pp.

ALTIERI, M.A. 1983. *Agroecology: The Scientific Basis of Alternative Agriculture.* Division of Biological Control, University of California, Berkeley. 162 pp.

ANDREWS, D.J. & KASAM, A.H. 1976. On the importance of multiple cropping in increasing world food supplies. Pp. 1-10 in Papendicks, R.I., Fenchez, T.A. & Triplett, G.B. (Eds.) *Multiple Cropping in Increasing World Food Supplies.* American Society of Agronomists Special Publication No. 27.

ASHTON, P.S. 1978. Crown characteristics of tropical trees. Pp. 519-615 in Tomlinson, P.B. & Zimmerman, M.H. (Eds.) *Tropical Trees as Living Systems.* Cambridge University Press, Cambridge.

BANSAL, R.C. & GREWAL, S.S. 1986. Studies on sedimentation of Sukhna Lake, Chandigarh. *Soil Conservation Annual Report.* Central Soil and Water Conservation Research and Training Institute, Dehradun.

BAZZAZZ, F.A. 1991. Regeneration of tropical forests: physiological responses of pioneer and secondary species. Pp. 91-118 in Gomez-Pompa, A., Whitmore, T.C. & Hadley, M. (Eds.) *Rainforest Regeneration and Management.* UNESCO-MAB Series, Parthenon Publications, Carnforth, Lancs. U.K.

BHADAURIA, T. & RAMAKRISHNAN, P.S. 1989. Earth worm population dynamics and contribution to nutrient cycling during cropping and fallow phases of shifting agriculture (jhum) in north-east India. *Journal of Applied Ecology* 26: 505 - 520.

BHADAURIA, T. & RAMAKRISHNAN, P.S. 1991. Population dynamics of earthworms and their activity in forest ecosystems of north-east India. *Journal of Tropical Ecology* 7: 305 - 318.

BOOJH, R. & RAMAKRISHNAN, P.S. 1982a. Growth strategy of trees related to successional status. I. Architecture and extension growth. *Forest Ecology and Management.* 4: 359 - 374.

BOOJH, R. & RAMAKRISHNAN, P.S. 1982b. Growth strategy of trees related to successional status. II. Leaf dynamics. *Forest Ecology and Management* 4: 375 - 386.

BOOJH, R. & RAMAKRISHNAN, P.S. 1982c. Growth and architecture of two altitudinal populations of *Schima wallichii.* Pp. 534-545 in *Proceedings of the Indian National Science Academy B48.*

BOOJH, R. & RAMAKRISHNAN, P.S. 1983a. Sacred groves and their role in environmental conservation. Pp. 6-8 in *Strategies for Environmental Management.* Souvenir Volume, Department of Science and Techology, Goverment of Uttar Pradesh, Lucknow.

BOOJH, R. & RAMAKRISHNAN, P.S. 1983b. The growth patterns of two species of *Schima. Biotropica* 15: 142 - 147.

BORTHAKUR, D.N., SINGH, A., AWASTHI, R.P & RAI, R.N. 1978. Shifting cultivation in the northeastern region. Pp. 330-342 in *Proceedings of a National Seminar - Resources, Development and Environment in the Himalayan Region.* Department of Science and Techology, Government of India, New Delhi.

BOSERUP, E. 1986. *The Conditions of Agricultural Growth.* Aldine, Chicago. 123 pp.

BROONKIRD, S.A., FERNANDES, E.C.M. & NAIR, P.K.K. 1984. Forest villages: an agroforestry approach to rehabilitating forest land degraded by shifting cultivation in Thailand. *Agroforestry Systems* 2: 87-102.

CHIN, S.C. 1982. The significance of rubber as a cash crop in Kenyah swidden village in Sarawak. *Federation Museum Journal* 27: 23 - 37.

CONKLIN, H.C. 1957. *Hanunoo Agriculture.* FAO Forestry Development Paper No. 21, FAO Rome. 109 pp.

DAZHONG, W. & PIMENTAL, D. 1984. Energy inputs in agricultural systems of China. *Agriculture, Ecosystems and Environment* 11: 29 - 35.

EUSSEN, E.H.H. & WIRJAHARDJA, S. 1973. Studies on alang-alang [*Imperata cylindrica* (L.) Beauv.] vegetation. *Biotropical Bulletin* 6 : 1 - 24.

EWEL, J. J. 1986. Designing agricultural ecosystems for the humid tropics. *Annual Review of Ecology and Systematics* 17: 245 - 271.

FAO. 1978. Shifting cultivation. *Forest News for Asia and the Pacific* 2 : 1 - 26.

FAO/SIDA. 1974. *Report on a Regional Seminar on Shifting Cultivation and Soil Conservation in Africa.* FAO, Rome. 248 pp.

GANGWAR, A.K. & RAMAKRISHNAN, P.S. 1987. Cropping and yield patterns under different land use systems of the Khasis at higher elevations of Meghalaya in north-eastern India. *International Journal of Ecological and Environmental Science* 13: 73 - 86.

GLIESSMAN, S. R., GARCIA, E. R. & AMADOR, A.M. 1981. The ecological basis for the application of traditional agricultural technology in the management of tropical agroecosystems. *Agro-Ecosystems* 7: 173 - 185.

GREWAL, S. S., MITTAL, S. P. & SINGH, G. 1990. Rehabilitation of degraded lands in the Himalayan foothills: peoples participation. *Ambio* 19: 45 - 48.

HARE, W. L., MARLOW, J. P., RAE, M. L., GRAY, F., HUMPHRIES, R. & LEDGAR, R. 1990. *Ecologically Sustainable Development.* Australian Conservation Foundation, Fitzroy, Australia.

HART, R.D. 1980. A natural analog approach to the design of a successional crop system for tropical environments. *Biotropica* 12 (Suppl.): 73 - 82.

HICKLING, C.F. 1961. *Tropical Inland Fisheries.* Longman, London.

HUNTLEY, B.J., EZCURRA, E., FUENTES, E.R., FUJI, K., GRUBB, P.J., HABER, W., WARGER, J.R.E., HOLLAND, M., LEVIN, S.A., LUBCHENKO, J., MOONEY, H.A., NOBLE, I., NORONOV, V., PULLIAM, R.H., RAMAKRISHNAN, P.S., RISSER, P.G., SALA, O., SARUKHAN, J., & SAMBROCK, W.G. 1991. A sustainable biosphere: the global imperative. *Proceedings of the Ecological Society of America Workshop.* Cuernavaca, Mexico. 10 pp.

KANG, B.T. & DUGUMA, B. 1984. Nitrogen management in alley cropping systems. *International Symposium on Nitrogen Management in Alley Cropping Systems.* International Institute of Tropical Agriculture, Ibadan, Nigeria.

KHIEWTAM, R.S. 1986. Ecosystem function of protected forests of Cherrapunji and adjoining areas. Ph.D. thesis, North Eastern Hill University, Shillong. 202 pp.

KOTHYARI, B.P., RAO, K.S., SAXENA, K.G., KUMAR, T. & RAMAKRISHNAN, P.S. 1991. Institutional development and transfer of water-harvesting technology in the Himalaya. Pp. 673-678 in Tsakins, G. (Ed.) *Advances in Water Resources Technology.* A.A. Balkema, Rotterdam, Netherlands.

KUSHWAHA, S.P.S., RAMAKRISHNAN, P.S. & TRIPATHI, R.S. 1981. Population dynamics of *Eupatorium odoratum* in successional environments following slash and burn agriculture. *Journal of Applied Ecology* 18: 529 - 535.

KUSHWAHA, S.P.S., RAMAKRISHNAN, P.S. & TRIPATHI, R.S. 1983. Population dynamics of *Imperata cylindrica* (L.) Beauv. var. Major related to slash and burn agriculture (jhum) in north-eastern India. *Proceedings of the Indian Academy of Science (Plant Science)* 92: 313 - 321.

LAMBERT, J.D.H. 1985. The ecological consequence of ancient Mayan agricultural practices in Belize. In Farrington, I.S. (Ed.) *Prehistoric Intensive Agriculture in the Tropics.* BAR International Series 232.

LANGENHEIM, J.H., OSMOND, C.B., BROOKS, A. & FERRAR, D.J. 1984. Photosynthetic responses to light in seedlings of selected Amazonian and Australian rainforest tree species. *Oecologica* 63: 215 - 224.

LEACH, G. 1976. *Energy and Food Production.* IPC Science and Technology Press, Guildford. 137 pp.

MAIKHURI, R.K. & RAMAKRISHNAN, P.S. 1990. Ecological analysis of a cluster of villages emphasizing land use of different tribes in Meghalaya in north-east India. *Agriculture, Ecosysetms and Environment* 31: 17 - 37.

MALHOTRA, K.C. & POFFENBERGER, M. 1989. *Forest Regeneration Through Community Protection.* West Bengal Forest Department, Calcutta. 47 pp.

MISHRA, B. K. & RAMAKRISHNAN, P. S. 1981. The economic yield and energy efficiency of hill agro-ecosystems at higher elevation of Meghalaya in north-eastern India. *Acta Oecologica - Oecological Applications* 2: 369 - 389.

MISHRA, B.K. & RAMAKRISHNAN, P.S. 1982. Energy flow through a village ecosystem with slash and burn agriculture in north-eastern India. *Agricultural Systems* 9: 57 - 72.

MISHRA, B.K. & RAMAKRISHNAN, P.S. 1983. Secondary succession subsequent to slash and burn agriculture at higher elevations of north-east India. I. Species diversity, biomass and litter production. *Acta Oecologica - Oecological Applications* 4: 95 - 107.

MISHRA, B.K. & RAMAKRISHNAN, P.S. 1984. Nitrogen budget under rotational bush fallow agriculture (jhum) at higher elevations of Meghalaya in north-eastern India. *Plant Soil* 81: 37 - 46.

MITCHELL, R. 1979. *An Analysis of Indian Agroecoystems.* Interprint, New Delhi. 180 pp.

NGUU, N.V. & PALIS, R.K. 1977. Energy input and output of modern and traditional cultivation systems in lowland rice culture. *Philippines Journal of Biology* 6: 1 - 8.

NYE, P.H. & GREENLAND, D.J. 1960. *The Soil Under Shifting Cultivation.* Technical communication No. 51, Commonwealth Bureau of Soils, Harpenden, England. 156 pp.

RAMAKRISHNAN, P.S. 1984. The science behind rotational bushfallow agriculture system (jhum). *Proceedings of the Indian Academy of Science (Plant Science)* 93: 379 - 400.

RAMAKRISHNAN, P.S. 1985a. Humid tropical forests. P. 39 in *Research on Humid Tropical Forests.* Regional meeting of the national MAB committee of central and south Asian countries. MAB India, Ministry of Environment and Forests, New Delhi.

RAMAKRISHNAN, P.S. 1985b. Tribal man in the humid tropics of the north-east. *Man in India* 65: 1 - 32.

RAMAKRISHNAN, P.S. 1986. Morphometric analysis of growth and architecture of tropical trees and their ecological significance. Pp. 209-222 in *Naturalia Monspeliensia-Colloquium International sur l'Arbore,* Montpelier.

RAMAKRISHNAN, P.S. 1987. Role of tree architecture in agroforestry. Pp. 112-130 in Khosla, P.K. & Khurana, D.K. (Eds.) *Agroforestry for Rural Needs.* Indian Society of Tree Scientists, Solan, India.

RAMAKRISHNAN, P. S. 1989. Nutrient cycling in forest fallows in north-eastern India. Pp. 337-352 in Proctor, J. (Ed.) *Mineral Nutrients in Tropical Forest and Savanna Ecosystems.* Blackwell Scientific Publications, Oxford.

RAMAKRISHNAN, P.S. 1992. *Shifting Agriculture and Sustainable Development: An Interdisciplinary Study From North-Eastern India.* MAB-Book Series, Vol. 10, UNESCO, Paris and Parthenon Publications, Carnforth, Lancs., U.K. 424 pp.

RAMAKRISHNAN, P.S. & DAS, A.K. 1983. Studies on pine ecosystem function in Meghalaya. *Tropical Plant Science Research* 1: 15 - 24.

RAMAKRISHNAN, P.S. & MISHRA, B.K. 1981. Population dynamics of *Eupatorium adenophorum* Spreng. during secondary succession after slash and burn agriculture (jhum) in north-eastern India. *Weed Research* 22: 77 - 84.

RAMAKRISHNAN, P.S. & RAM, S.C. 1988. Vegetation, biomass and productivity of seral grasslands of Cherrapunji in north-east India. *Vegetatio* 74: 47 - 53.

RAMAKRISHNAN, P. S. & SAXENA, K. G. 1984. Nitrification of Cherrapunji. *Current Science* 53: 107 - 109.

RAMAKRISHNAN, P.S. & TOKY, O.P. 1981. Soil nutrient status of hill agro-ecosystems and recovery patterns after slash and burn agriculture (jhum) in north-eastern India. *Plant Soil* 60: 41 - 64.

RAMAKRISHNAN, P.S. & VITOUSEK, P.M. 1989. Ecosystem-level processes and the consequences of biological invasions. Pp. 281-300 in Drake, J.A., Mooney, H.A., di Castri, F., Groves, R.H., Kruger, F.G., Rejmanek, M. & Williamson, M. (Eds.) *Biological Invasions: A Global Perspective.* John Wiley & Sons.

RAMAKRISHNAN, P.S. , SHUKLA, R.P. & BOOJH, R. 1982. Growth strategies of trees and their application to forest management. *Current Science* 51 : 448 - 455.

RAMAKRISHNAN, P.S. , TOKY, O.P., MISHRA, B.K., & SAXENA, K.G. 1981. Slash and burn agriculture in north-eastern India. Pp. 570-586 in Mooney, H., Bonnickson, T.M., Christensen, N.L., Lotan, J.E. & Reiners, W.A. (Eds.) *Fire Regimes and Ecosystem Properties.* USDA Forest Service General Technical Report, W.O. 26, Washington D.C.

RAO, K.S. & RAMAKRISHNAN, P.S. 1987. Socio-economic ananlysis of bamboo resourcs in East Khasi hills district of Meghalaya. *Man in India* 67: 221 - 231.

RAO, K.S. & RAMAKRISHNAN, P.S. 1989. Role of bamboos in nutrient conservation during secondary succession following slash and burn agriculture (jhum) in north-east India. *Journal of Applied Ecology* 26: 625 - 633.

RAPPAPORT, R.A. 1971. The flow of energy in an agricultural society. *Scientific American* 225: 117 - 132.

RUTHENBERG, H. 1976. *Farming Systems in the Tropics*. Clarendon Press, Oxford, U.K. 366 pp.

SANCHEZ, P.A. & BUOL, S.W. 1976. Soils of the tropics and the world food crisis. *Science* 188: 598 - 603.

SARABHAI, K.V., RAJU, G., DESAI, K., KATHOORIA, P. & KHANDELWAL, R. 1990. Buffer zone restoration in India. Nelirin Foundation for Development, Ahmedabad, India. 115 pp. (Mimeo).

SAXENA, K.G. & RAMAKRISHNAN, P.S. 1982. Reproductive efficiency of secondary successional herbaceous populations subsequent to slash and burn of sub-tropical humid forests in north-eastern India. *Proceedings of the Indian Academy of Science (Plant Science)* 91: 61 - 68.

SAXENA, K.G. & RAMAKRISHNAN, P.S. 1983a. Growth and allocation strategies of some perennial weeds of slash and burn agriculture (jhum) in north-eastern India. *Canadian Journal of Botany* 61: 1300 - 1306.

SAXENA, K.G. & RAMAKRISHNAN, P.S. 1983b. Growth, resource allocation patterns and nutritional status of some dominant annual weeds of shifting agriculture (jhum) in north-eastern India. *Acta Oecologica - Oecological Applications* 4: 323 - 333.

SAXENA, K.G. & RAMAKRISHNAN, P.S. 1984a. Herbaceous vegetation development and weed potential in slash and burn agriculture (jhum) in north-eastern India. *Weed Research* 24: 135 - 142.

SAXENA, K.G. & RAMAKRISHNAN, P.S. 1984b. C_3/C_4 species distribution among successional herbs following slash and burn in north-eastern India. *Acta Oecologica - Oecological Applications* 5: 335 - 346.

SAXENA, K.G. & RAMAKRISHNAN, P.S. 1986. Nitrification during slash and burn agriculture (jhum) *Acta Oecologica - Oecological Applications* 7: 307 - 319.

SEAVOY, R.E. 1973. The transition to continuous rice cultivation in Kalimantan. *Annals of the Association of Amercian Geographers* 63: 522 - 528.

SHUKLA, R.P. & RAMAKRISHNAN, P.S. 1982. Comparitive study on field germination and establishment of early vs. late successional trees in north-eastern India. Pp. 115 - 120 in *Proceedings of the Indian National Science Academy* B 48.

SHUKLA, R.P. & RAMAKRISHNAN, P.S. 1984a. Leaf dynamics of tropical trees related to successional status. *New Phytology* 97: 697 - 706.

SHUKLA, R.P. & RAMAKRISHNAN, P.S. 1984b. Biomass allocation strategies and productivity of tropical trees related to successional status. *Forest Ecology and Management* 9: 315 - 324.

SHUKLA, R.P. & RAMAKRISHNAN, P.S. 1986. Architecture and growth strategies of tropical trees in relation to successional status. *Journal of Ecology* 74: 33 - 46.

SINGH, J. & RAMAKRISHNAN, P.S. 1982. Structure and function of a sub-tropical humid forest of Meghalaya. I. Vegetation, biomass, and its nutrients. *Proceedings of the Indian Academy of Science (Plant Science)* 91: 241 - 253.

SPENCER, J.E. 1966. *Shifting Cultivation in South-Eastern Asia*. Publications in Geography No. 199. University of California. 247 pp.

STEINHART, J. S. & STEINHART, C.E. 1974. Energy use in the U.S. food system. *Science* 184: 307 - 316.

SWAMY, P.S. & RAMAKRISHNAN, P.S. 1987a. Weed potential of *Mikania micrantha* H.B.K., and its control in fallows after shifting agriculture (jhum) in north-east India. *Agriculture, Ecosystems and Environment* 18: 195 - 204.

SWAMY, P.S. & RAMAKRISHNAN, P.S. 1987b. Contribution of *Mikania micrantha* H.B.K. during secondary succession following slash and burn agriculture (jhum) in north-east India. II. Nutrient cycling. *Agriculture, Ecosystems and Environment* 22: 239 - 249.

SWAMY, P.S. & RAMAKRISHNAN, P.S. 1988a. Effect of fire on growth and allocation strategies of *Mikania micrantha* under early successional environments. *Journal of Applied Ecology* 25: 653 - 658.

SWAMY, P.S. & RAMAKRISHNAN, P.S. 1988b. Ecological implications of traditional weeding and other imposed weeding regimes under slash and burn agriculture (jhum) in north-eastern India. *Weed Research* 28: 127 - 136.

TOKY, O. P. & RAMAKRISHNAN, P. S. 1981a. Cropping and yields in agricultural systems of the north-eastern hill region of India. *Agro-Ecosystems* 7 : 127 - 136.

TOKY, O.P. & RAMAKRISHNAN, P.S. 1981b. Run-off and inflitration losses related to shifting agriculture (jhum) in north-eastern India. *Environmental Conservation* 8: 313 - 321.

TOKY, O.P. & RAMAKRISHNAN, P.S. 1982. A comparitive study of the energy budget of hill agro-ecosystems with emphasis on the slash and burn system (jhum) at lower elevations of north-eastern India. *Agricultural Systems* 9: 143 - 154.

TOKY, O.P. & RAMAKRISHNAN, P.S. 1983. Secondary succession following slash and burn agriculture in north-eastern India I. Biomass, litterfall and productivity. *Journal of Ecology* 71: 735 - 745.

WHITMORE, T.C. 1978. Gaps in the forest canopy. Pp. 639 - 655 in Tomlinson, P.B. & Zimmerman, M.H. (Ed.) *Tropical Trees as Living Systems.* Cambridge University Press, Cambridge, U.K.

WHITMORE, T.C. 1983. Secondary succession from seed in tropical rainforests. *Forestry Abstracts* 44: 769 - 779.

WHITMORE, T.C. 1984. *Tropical Rain Forests of the Far East.* Oxford University Press, Oxford, U.K. Second edition.