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A THREE DIMENSIONAL DYNAMIC MODEL OF DAMAR AGROFOREST IN SUMATRA (INDONESIA)

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1. BACKGROUND and GENERAL OBJECTIVES

This study is part of a broader program on Indonesian cultivated forests which has started more than 10 years ago (DE FORESTA & MICHON 1990 et 1994, GOUYON et al. 1993, MARY & MICHON 1987, MICHON 1985, MICHON & BOMPARD 1987, MICHON et al. 1995). These agroforests usually show a high botanical richness and a multi-layered vertical structure quite close to natural rainforest. Different types of agroforests may be distinguished according to the main tree species. The dominant species may be damar trees (*Shorea javanica*) tapped to collect resin, *Hevea brasiliensis* grown for latex, fruit trees (duku, durian, rambutan, jacktree, etc.) or timber trees. Numerous secondary species yield many different resources (fibers, vegetables, spices, medicines, etc.) some of which being commercialized.

damar agroforests are probably the most studied and therefore the best known agroforests. These agroforests are facing rapid changes due (in particular) to the emergence of a new market for damar wood. Thereafter logging activity is getting more and more common. Is this new activity ecologically sustainable and under what conditions ? Such is, very schematically, the type of questions we are asked. In other words our main concern lies in the conditions of viability of this agroforestry strategy to manage forest resources, and ultimately the conditions of transposability of such a strategy. We focus here on the ecological constraints of the system. Nevertheless we do believe that social and economic characteristics are often of prime importance in determining wether the biological potential can be realized by farmers living in the real world.

2. HYPOTHESES AND METHOD

2.1. Basic assumptions

The very complex structure of the natural forest (and to a lesser extent of the agroforest) illustrates the intense competition for light that goes on in this environment, in which other climatic factors are not limiting at any time of the year, allowing vegetation to achieve an extraordinary luxuriance and biomass (LEIGH 1975). The amount of sunlight filtering through the many layers of foliage in a tropical rain forest is small: less than 1 % of the light perceived at the top of the canopy reaches the ground (ALEXANDRE 1982). The importance of gaps in the canopy which provide temporarily well-illuminated places at ground level is vital to the regeneration of most of the forest constituent plants (RIERA 1995). Other factors such as nutrient availability may be limiting and may affect overall growth nevertheless competition for light is certainly a key factor in orienting the dynamic of the natural rain forest. Can light be assigned such an important role in orienting dynamics in Damar agroforest ? If so, is the crown position inside the canopy a good indicator of the light received by a tree ? If not what other major ecological characteristics should be considered in order to optimize agroforest design and management ? Understanding agroforest dynamics may as well give us some insight in processes going on in natural forests. Yet from a practical point of view agroforest show two major advantages over natural forests. The specific composition is much simpler (indeed 4 or 5 different species may account for as much as 90% of the total population) and significant indigenous knowledge on the ecology of the different species is readily available from the farmers.

2.2. Modeling technique

An important characteristic of the present situation lies in its instability: sylvicultural practices are changing rapidly due to the changing social and economic environment. Another characteristic of these agroforests is the spatial heterogeneity which is a consequence of the complex structure of the multi-species forest but also of the small size of the parcels of land combined with a great variety of sylvicultural practices. Therefore classical modeling techniques of population dynamics using transition matrices, or integro-differential formalism seem to be inadequate as they are limited in dealing with spatio-temporal variability,. An individual-based model seems well suited to the present case (see HUSTON et al. 1988, and DE ANGELIS & GROSS 1992 for some general references on individual based modeling). Indeed such a model is designed at a local scale and thus can take into account the variability encountered. In such a bottom-up approach, population dynamics characteristics such as recruitment or mortality, result from the interaction of the elementary components (i.e. the trees). Of course, the first step in such an approach is to make clear in what way the trees interact. A computer program may then be used as a virtual laboratory to test the hypotheses made or to explore new situations, etc. It may also be used to assess the analytical techniques (in particular statistical techniques) used to study the real world by testing them on the entirely controlled and reconstructed artificial ecosystem.

3. MODEL

3.1 Outline

At the present stage the model is just a demonstration model with only abstract connections with real world. The model simulates on a one hectare plot and on a yearly basis the functioning of a virtual patch of forest made of 4 different tree species with different ecological requirements. Border effects are handled by considering a toric representation of the plot surface[1] : trees on one edge are considered as neighbors of the trees of the opposite edge of the quadrangular plot. Each tree species obeys to specific rules governing recruitment, growth and death. These rule are parameterised according to the local conditions of growth prevailing for each tree. The program is developed using VisualWorks, an object oriented language. The outputs of the model include population characteristics for the different species, such as the distribution of crown radius, distribution of tree height, distribution of crown position and crown form indices, mortality census, etc., and individual characteristics such as growth curves. A real time graphic visualization allows the user to inspect any subgroup of trees at anytime by selecting them with the mouse on a map of the plot. A simple parallel projection of the selected subgroup of trees is also available. Such a graphic interface proved to be useful during the sensitivity analysis at a local scale.

3.2 Tree characteristics

A set of variables is assigned to each tree. Some of them are strictly individual, some are common to all the trees of the same species. Species attributes include a subset of geometrical parameters that define the general crown shape (relation between horizontal and vertical crown radii), the allometric relation between crown extension and tree height in optimal growing conditions, maximum crown extension and maximum tree height. The way in which the tree reacts to its environment (tolerance to shade and full sunlight at different stages) is also defined at the specific level. Potential growth curves are also determined at the species level. Individual tree attributes include geographical coordinates, current dimension and age, record of previous growth and a list of neighbors. Two additional variables are calculated at each time step for every tree from the former variables : a Crown Form index and a Crown Position index.

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[1] A torus may be defined as the R^3 surface generated by the rotation of a circle around a straight line belonging to the circle's plan but not intersecting with the circle.

3.3 Growth

At each step in time, an attempt to grow is made by every tree. Growth is successful if no collision arises between the growing tree crown and neighboring crowns. Growth is computed in a two step process. First an attempt is made to grow in height. If growth in height is successful then an attempt is made to increase the crown volume.

Both height increment and crown radius increment follow Chapman-Richards functions, broadly used to describe tree growth, which an expression of the form:

$$\text{(i) } x = a * (1 - b*\exp(-k*t))^{c}$$

where k is a scale factor, a the asymptotic value, b and c parameters responsible for the shape of the growth curve.

Identifying finite difference and differential, (i) may be rewritten with as the rate of change per unit of time

$$\text{(ii) } \Delta x = c * k * x * ((a/x)^{(1/c)} - 1)$$

In this form, the growth increment no longer depends on age but only on size. Thus, it becomes possible to untie age and growth rate and account for temporary stops or pronounced slowdowns in growth which may occur in unfavorable conditions when space or light resources become insufficient. A vigorous re-growth may occur once better conditions are recovered. (CLUZEAU 1992, SCHUTZ 1989). Nevertheless, this compression ability and the speed at which a tree will recover depends on the tree species. Such refinements may incorporated in later versions.

Growth in diameter may also be defined as following a Chapman-Richards function but has not yet been implemented. Parameters for the different species were set as shown in table 1.

	Height			crown	vertical	radius
	c1	**a1**	**k1**	**c2**	**a2**	**k2**
		(m)	**(yr^{-1})**		**(m)**	**(yr^{-1})**
Damar	2	48	0.04	1.22	12	0.04
Durian	2	48	0.04	1.74	18	0.04
Duku	2	30	0.02	2	12.5	0.02
Pioneer	2	30	0.08	2	2	0.08

table 1 : Default growth parameters for the different species (see text for explanation)

Horizontal crown radius (hr) is computed as a function of the vertical radius (vr).

Damar	hr = vr * (1/9+2/17*vr)
Duku	hr = vr / 2
Durian	hr = vr / 2
Pioneer	hr = vr*4

table 2: Relation between horizontal crown radius (hr) and vertical crown radius vr

These functions define the maximum potential growth. This potential growth is restricted by stress indices to calculate the actual growth. Following the pioneering work of DAWKINS (1958, ALDER & SYNNOT 1992) we consider two types of growth reducers. The first one is a function of the Crown Form index and the second one a function of the Crown Position index. The former index is an architectural characteristic and reflects the development history of the tree. The latter, which depends on the relative position of the crown within the canopy, reflects the conditions of growth prevailing at a particular moment.

The Crow Form index merely measures the relative development of the crown compared to the total height of the tree. It is indicative of the general vigor of the tree. It may be correlated both to growth increment and mortality (see DAWKINS 1966 in GOURLET-FLEURY 1992). The following Crown Form scores are defined (ALDER & SYNNOT 1992):

5 = Perfect. The best size and development generally seen, wide, circular in plan, symmetrical

4 = Good: Very near ideal, sylviculturally satisfactory, but with some slight defect of symmetry or some dead branch tips.

3 = Tolerable. Just sylviculturally satisfactory, distinctly asymmetrical or thin, but apparently capable of improvement if given more space.

2 = Poor: Distinctly unsatisfactory, with extensive dieback, strong asymmetry and few branches but probably capable of surviving.

1 = Very Poor: Definitely degenerating or suppressed, or badly damaged, and probably incapable of increasing its growth rate or responding to liberation.

In this classification the degree of symmetry of the crown appears to be a key factor. Indeed restriction in growth of the crown is often asymmetrical when it is related to over-crowding of the surrounding space. Nevertheless, in the model, in order to reduce computing time crown is kept symmetrical around its vertical axis. A crown with poor Crown Form index will thus be represented as shrunk instead of asymmetrical (a situation rather common in dense plantations for example, where competition for space may be considered as isotropic in first approximation). The crown form index is simply computed as the ratio between the actual crown volume and the potential crown volume defined by the actual height, rounded to the nearest lower integer multiplied by 5.

The first stress index called *red*1 is a simple linear function of the Crown Form index (CF) and varies between 1/5 and 1. The same stress index is applied to growth in height and crown enlargement.

(iii) $red1 = CF/5$

The Crown Position index is indicative of the competitive status for light interception, it is based on DAWKINS crown classification (1958).

5 = Emergent: Crown plan exposed vertically and free from lateral competition at least within the 90° inverted cone subtended by the crown base.

4 = Full overhead light: Crown plan fully exposed vertically but adjacent to other crowns of equal or greater height within the 90° cone.

3 = Some overhead light: Crown partially shaded vertically but main axis not overtopped.

2 = Some side light: Main axis overtopped (little overhead light) but at least one third of the 24 sampled directions around the tree (12 azimuths combined with 2 inclinations 45 and 75 degrees) is free from neighboring crown.

1 = No direct light: Main axis overtopped and more than 2/3 of the surrounding directions are not free from neighboring crowns.

Two stress indices are calculated using the Crown Position index. One applies to the growth in height and the other one applies to the growth of the crown radius. These stress indices are calculated according to the temperament of each species. For example, a shade tolerant species will not benefit much from a full exposition to sunlight. On the other hand a light demanding species will suffer much more from a bad Crown Position index.

The proposed general expression of *red2* (height reducer) and *red3* (crown extension reducer) are as follow (and see figure 1):

(iv) *red2* or *red3* = $(CP/5)^i$ with $i>1$ for light demanding species, $i<1$ for shade tolerant species, and $i=1$ for intermediate.

Default values were set as indicated below.

Pioneer tree : *red2=red3=* $(CP/5)^2$ species very sensitive to shading
Duku : *red2=red3=* $(CP/5)^{0.5}$ shade tolerant species
Durian, Damar : *red2* =1, *red3* = CP/5 intermediate requirement for light

In the case of Damar and Duku there is no direct reduction in height growth resulting from poor Crown Position index. The tree continues to grow in height but since the crown extension is reduced, the Crown Form index in turn soon suffers from this increase in slenderness and ultimately growth in height may be reduced.

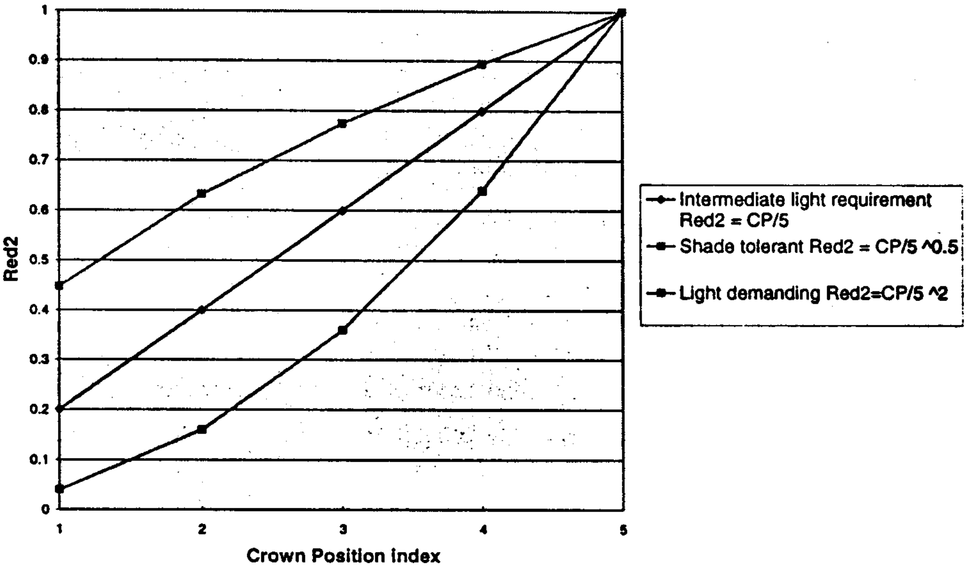


figure 1: Growth reducer red2 as a function of the Crown Position index

3.4. Recruitment

The earliest development stage considered in the model is the sapling stage (no seeds nor seedlings). Recruitment procedure is split into two separate steps. The first step consists in making the decision of recruitment, the second step is the attempt at recruitment.

The decision of recruitment may result from global characteristics (such is the case for Damar and Duku) or local characteristics (such is the case for Pioneer species). In case of non Pioneer species, the number of attempts at recruitment of a tree of a given species is a linear function of the number of trees which have reached the reproductive stage (recruitment rate is set to be equal to 0.05 for all three species). This stage is defined as a given age for the different species (15 years for Duku and Durian, 25 years for Damar). It should be stressed that regeneration is not an entirely natural process. It is even largely controlled in the case of Damar which is often planted. Specific algorithms at the step of making a decision of recruitment should be developed to simulate the management by the farmer (planting, clearing,...).

Once the decision of recruitment is made an attempt at recruitment is made. Recruitment will be successful if the new sapling crown does not collide with any existing crown (the same constraint applies to all species) and if its Crown Position index is propitious, which depends on the species temperament. Favorable CP index for Damar and Durian was set between 2 and 5, while it was set between 1 and 4 for Duku which is supposedly less tolerant to intense exposure to sunlight during the early stages of development.

To manage the case of the Pioneer species whose individuals settle in open space the plot is divided into elementary quadrats of 10m x 10m. If a quadrat stays free at the ground level for 5 time steps then an attempt of recruitment of a Pioneer tree is made. Recruitment is successful if the new crown does not collide with other crowns and if the Crown Position index is at least equal to 4 (need for high irradiance). The 5 time steps lag stands for the 5 year period needed for a germinating seed to become a young sapling of a few meters high.

3.5. Mortality

Mortality may be "primary" or due to tree fall. Primary mortality is simulated by applying a survival test at each iteration to each tree. It is well known that seedlings and young saplings suffer high mortality rates (ROLLET 1969, SARUKHAN 1980, SWAINE 1989). Nonetheless mortality has repeatedly been reported to be independent of tree size for tree measuring more than 10 cm of Diameter at Breast Height (SWAINE 1989, MANOKARAN & KOCHUMEN 1987). Thus this survival probability is set independent of the tree size in the model since only saplings and later stages are considered.

Mortality has been reported to be correlated with growth rate (SWAINE 1989) and has often been used as a survival predictor by modellers : BUCHMAN 1979, EK & MONSERUD 1979, HANN 1980, BUCHMAN et al. 1983, WAN RAZALI 1988 in VANCLAY 1990. Thus the annual survival probability S is computed as a function of stress indices. Each time step a random number r in [0,1] is drawn for each individual and the tree is supposed to survive if $r < S$.

(v) for a Pioneer tree : $S = 0.995 * (((CF/5) * (CP/5)^2))^{0.025}$ (figure 1a)

(vi) for Duku : $S = 0.995 * ((CF/5) * (1.2- CP/5)^{0.025}$(figure 1b)

(vii) for Durian and Damar: $S = 0.995 * (CF/5)^{0.025}$

The shape of these functions are shown on figure 2 for Pioneer and Duku.

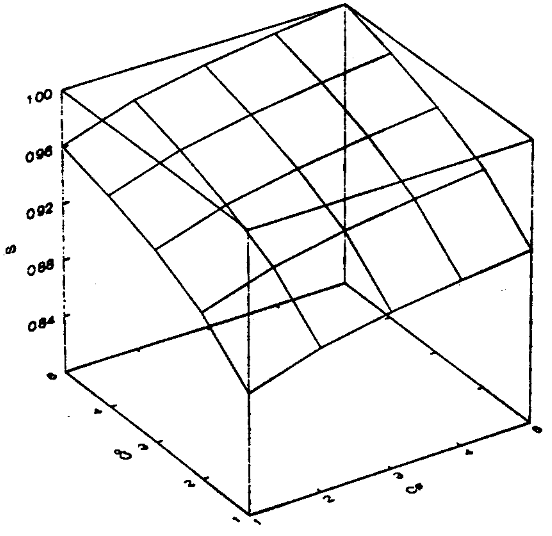


Figure 2a : Pioneer survival probability as a function of Crown Position (CP) and Crown Form (CF) indices.

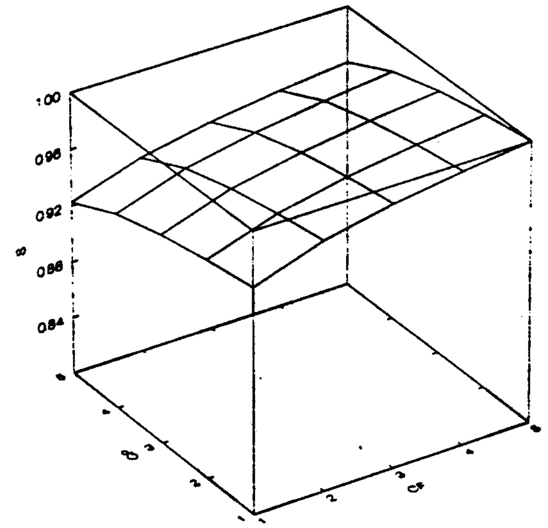


Figure 2b : Duku survival probability as a function of Crown Position (CP) and Crown Form (CF) indices.

Pioneer trees are submitted to increased mortality in case of low Crown Position index. This reflects their strict dependence on high light regimes. On the contrary Duku are submitted to increased mortality in case of high Crown Position index, as it is a typical understorey species.

Sylvicultural practices (age of first tapping, frequency of tapping, logging, etc.) will undoubtedly have some influence on the survival probability and should be taken into account in later versions. Varying life expectancies between species should also be dealt with explicitly in later versions.

Secondary mortality, due to tree fall, is also considered. When a tree falls the following algorithm is applied with a constant probability (0.5). A direction of fall is randomly chosen. All neighboring trees located in a 60° sector whose radius is equal to the height of the fallen tree are submitted to a survival test with a constant probability of 0.5, if their height is less than the height of the fallen tree. It would also be possible to consider lighter damages due to tree fall such as branch breakage by reducing CF.

4/ PRELIMENARY RESULTS

4.1. Sensitivity analysis

Planting density

The outcome of competition between two or more neighboring trees appears to be very sensitive to the planting distance. Figure 3a shows the silhouette of 6 Damar trees planted two by two at varying distances, after 100 time steps. For the sake of convenience recruitment or were prevented during this simulation. Similarly, trees are dealt with in the same fixed order during the whole simulation whereas normally this order is randomly changed at each time step.

When planted 3 m apart neither of the trees takes a definite advantage on the other and both grow slowly in height but fail to develop their crown to any significant extent. Planted 5 m apart, one tree quickly surpasses its rival in height and soon becomes dominant. When 9 m apart, again one tree surpasses the other in height but not enough to overtake it. Finally the lower tree has the more developed crown.

Competition occurs for space and light. The critical point here is probably competition for space. When the crowns of two neighboring trees of same height come into contact, the ability of a tree to overtop and then overtake its rival will depend on the rate of the growth in height at that moment and on the crown shape (mainly the lateral curvature radius). The interesting point here is that the response to increasing distance between trees is not continuous nor even monotonous.

Crown shape

The same spacing pattern applied to Durian which has the same temperament as Damar but different geometrical characteristics, lead to a different outcome as shown in figure 3b. In this case, the first tree to grow always overtops the other but the latter may or may not become suppressed depending on the distance between the trees. Contrary to Damar crown which flattens with aging, Durian crown has a fixed shape (see table 2). This shape determines a curvature radius inferior to Damar at an early stage, but superior to Damar at a later stage. Figure 3c and 3d show the patterns found for competing Duku trees and competing Pioneer trees in similar conditions. In the first case no stratification occurs, whereas it is systematically the case for Pioneer trees. Here the growth rate (low for Duku and high for the Pioneer tree) and the crown shape (ellipsoid with its big axis vertical for Duku, and big axis horizontal for the Pioneer tree) combine to give the patterns shown on figure 3c and 3d.

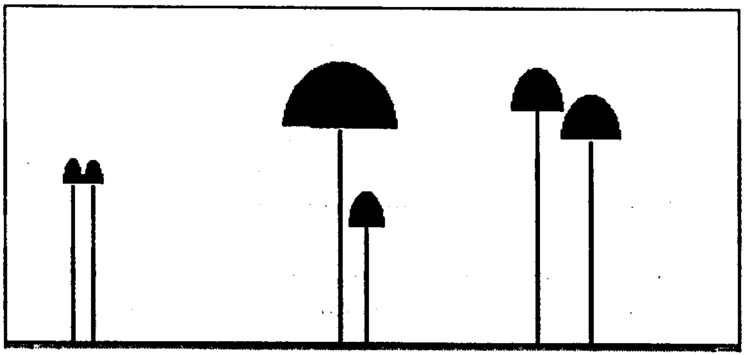


figure 3a: Damar

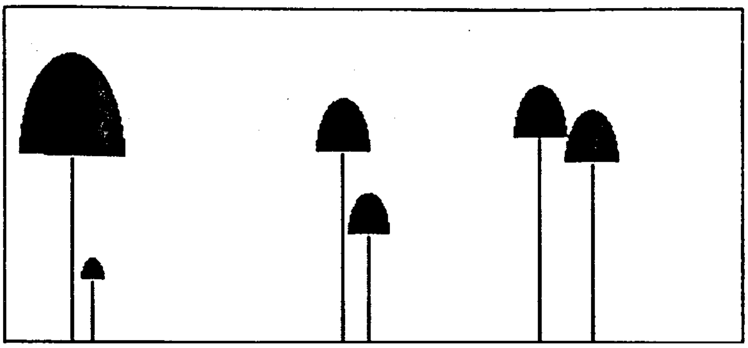


figure 3b: Durian

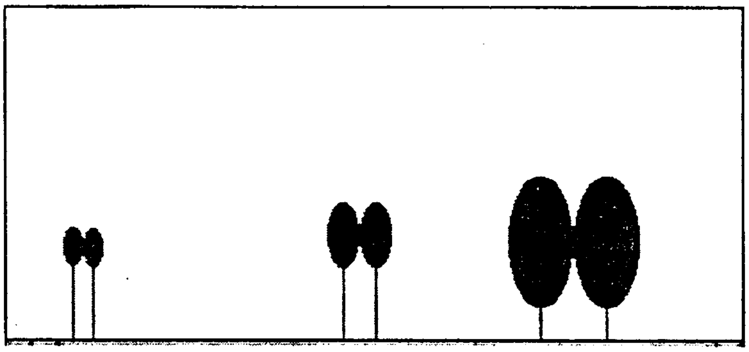


figure 3c: Duku

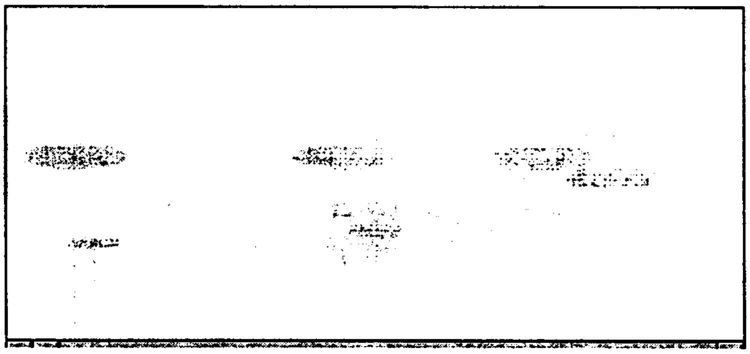


figure 3d: Pioneer

__figure 3__: Effect of planting distance on competition (100 time steps)

Crown Form index

CF index is computed as a function of the ratio of the actual crown volume to the potential crown volume. This leads to consider as belonging to class 1 trees with a crown volume less than 20 percent of the potential crown volume. This is equivalent to a crown radius less than 58 percent ($0.2^{0.33}$) of the potential crown radius. It is likely that this class is too broad : it is rather counter intuitive that trees with half the potential crown radius would have just the same behavior as trees with one tenth of the potential crown radius.

CF index directly influences mortality rate through the mortality function (see 3.5). As such it is a very sensitive parameter. When mortality and recruitment is precluded then the effect of CF on the dynamic of growth itself may be assessed. A comparison between two simulations using two different ways of computing the CF index (either as a function of the ratio of the actual crown volume to the potential crown volume or as the same function of the ratio of the actual crown radius to the potential crown radius) reveals only minor differences in growth dynamic during 100 time steps. This is related to the fact that CF index affects growth of all tree species in the same way (see 3.3). Thus the major influence of CF seems to be on mortality rate.

Distance of interaction

The standard distance of interaction was set to 50 m. This value is derived from the way the Crown Position index is computed : a 45 degree angle between the bottom of the crown of the smallest tree and the top of the crown of the biggest possible tree would put them at a distance of 47 m. The calculation of the mortality due to tree fall also makes use of the neighbors in a sector of 48 m radius (maximum height).

Since the number of potentially interacting trees increases like the second power of the distance of interaction, it is worthwhile trying to reduce this interaction distance in order to reduce computation time. Preliminary tests have shown that, apart from the effect on mortality rate (mediated through the computation of secondary mortality), the distance of interaction may well be reduced to 20 m without major changes in overall dynamics. Should this result be confirmed, it would then be useful to address tree fall damages by keeping track of the current spatial distribution of trees by means of a discrete representation of space (record of cells in a grid) instead of a list of neighbors.

4.2. General behavior

General model behavior is at first sight rather satisfactory. Crown radius, Crown Position and Crown form index distributions seem to have reasonable shape, total number of trees and overall dynamics of growth also compares well to the available data from permanent plots. Individual growth curves shows a high variability as expected (see Figure 4). Nonetheless some outputs require further examination.

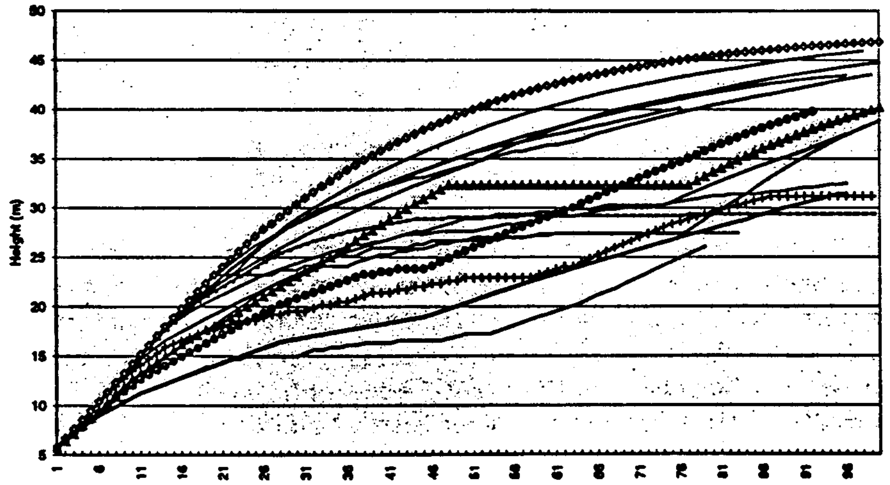
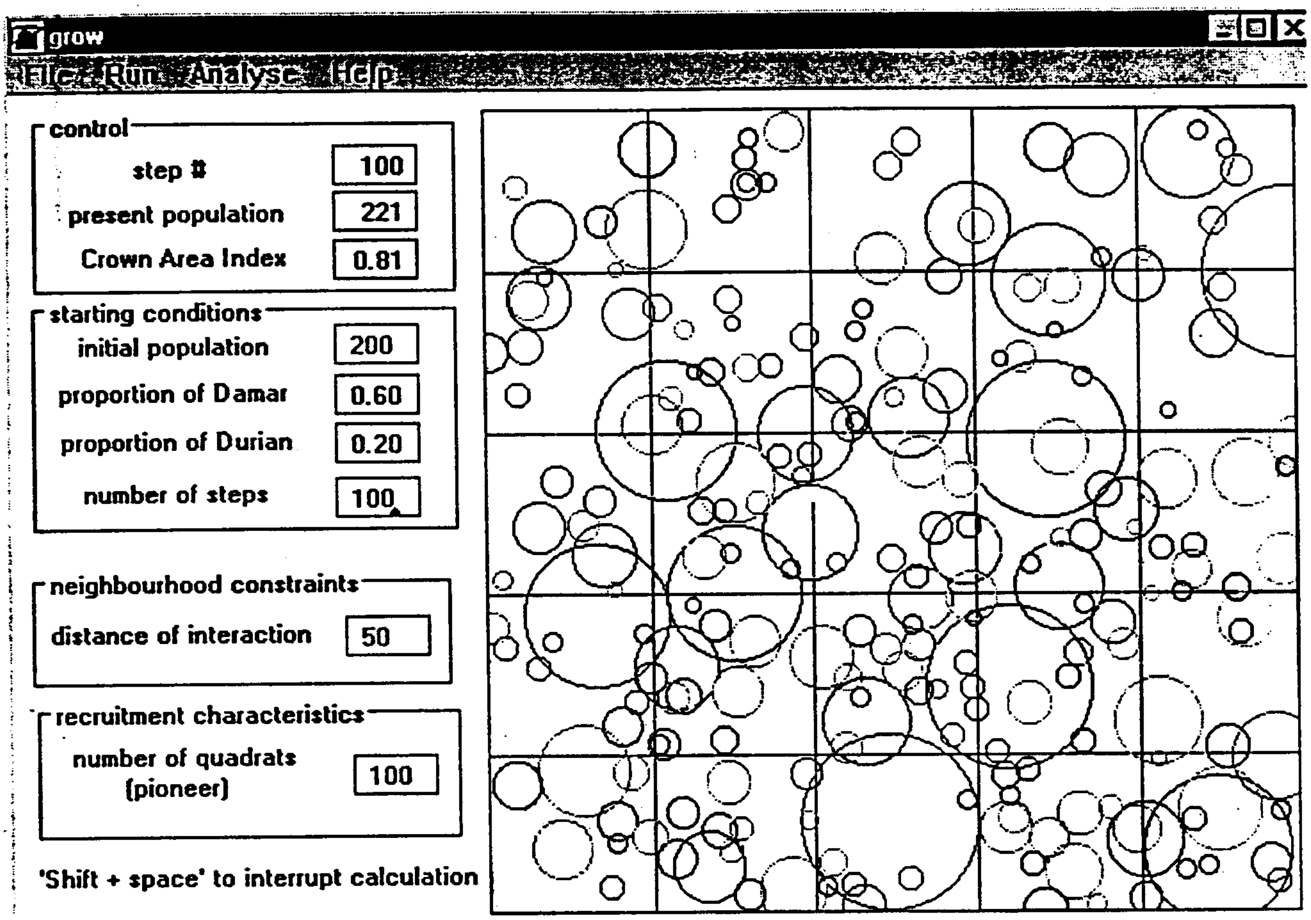


figure 4 : Sample of simulated growth curves in height for Damar

Crown Area Index

The CAI is computed as the ratio of the sum of all crown projections on the ground to the total ground area. CAI after 100 time steps reaches 0.8 which seems rather low. Of course the CAI is strongly constrained by the symmetrical shape of the trees whereas in the real world trees may show strong asymmetrical growth to fill adjacent gaps in the canopy. Nevertheless, a single layer of non overlapping adjacent discs of a fixed size would cover about 75 percent of the area irrespective to their size. A combination of circles of different sizes would then cover even more than 75 percent of the area. Thus one would expect a two layer canopy to reach a CAI of ca 1.5. The low value of CAI may be due to the high number of gaps one can notice on a map of a typical simulated plot (see Figure 5). This may result in part from the randomized location of recruited seedling whereas in a managed forest these seedlings whether planted or selected certainly do not follow a randomized pattern. But this may also result partly from too high mortality rates.



control

step # 100

present population 221

Crown Area Index 0.81

starting conditions

initial population 200

proportion of Damar 0.60

proportion of Durian 0.20

number of steps 100

neighbourhood constraints

distance of interaction 50

recruitment characteristics

number of quadrats (pioneer) 100

'Shift + space' to interrupt calculation

figure 5: A map of a simulated plot after 100 time steps.

Mortality rates

Average mortality rates for different species are shown on figure 6. The mean overall mortality rate is *ca.* 2% which is quite high. A careful examination of available data to assess the relative importance of primary versus secondary mortality, and mortality due to felling versus natural mortality has still to be done. Recruitment rates and location of new saplings should also receive careful attention. Figure 6 exhibits rather lower mortality rates for Duku and Pioneer trees in the first (and more numerous) class. This is probably related to the distribution of Crown Form indices of these species which are severely right skewed compared to the others (see Figure 7). This is due to the fact that growth in height parallels crown extension in case of inadequate light regime contrary to the case of Damar and Durian. This compensates for the increased mortality due to sensitivity to Crown Position index (see 3.5). As a consequence specific composition evolves only slowly over time (see figure 8).

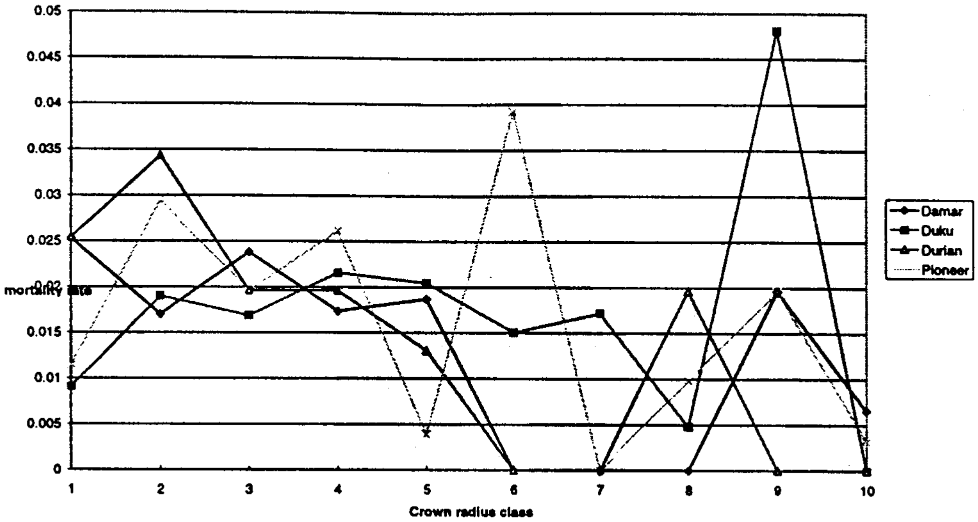


figure 6: Mean mortality rates between simulation steps 100 and 150.

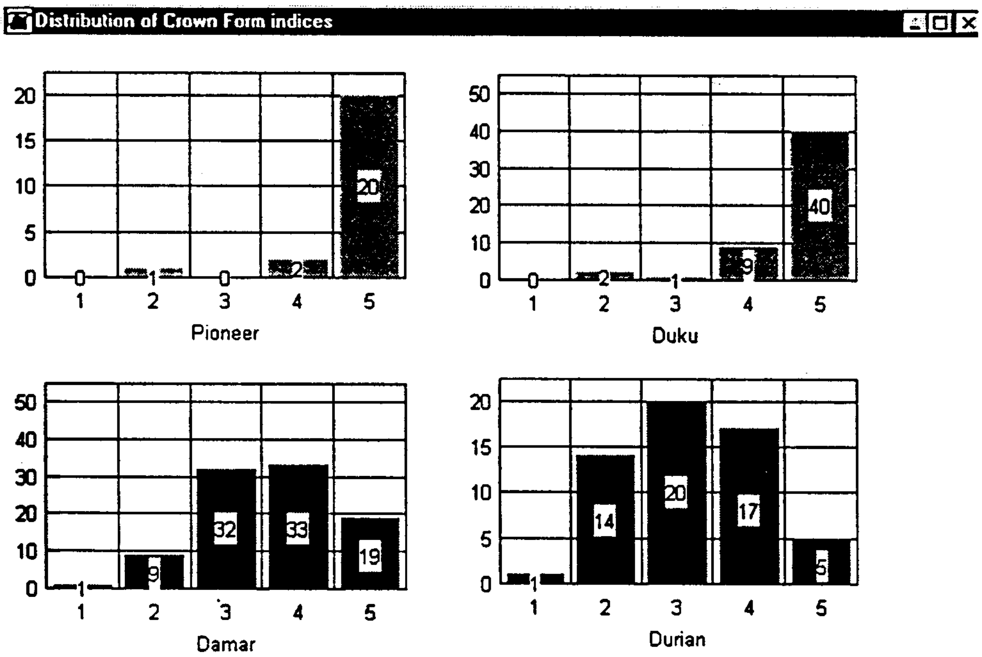


figure 7: Typical distributions of Crown Form indices after 150 time steps.

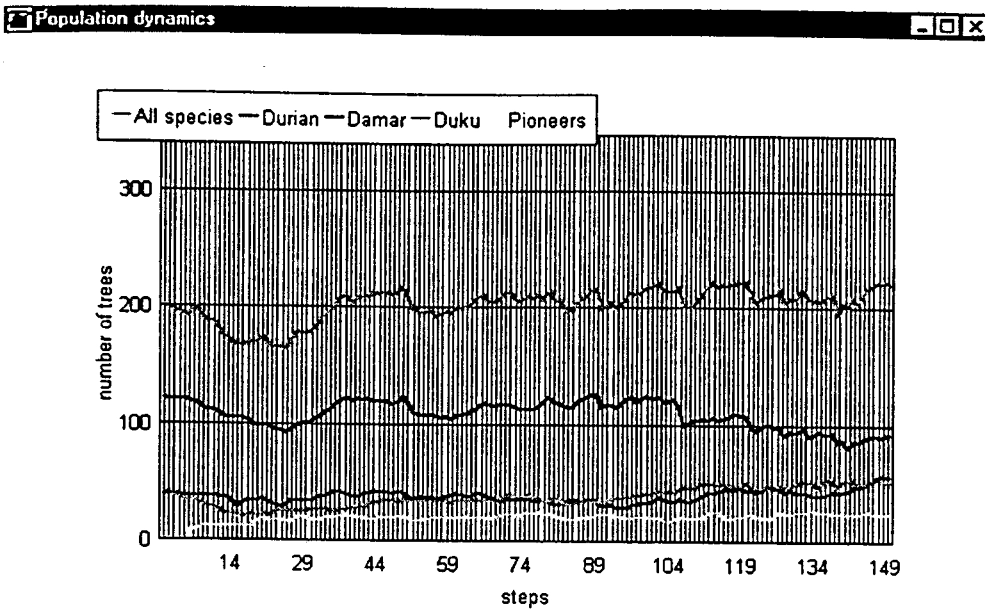


figure 8: Specific composition evolution across 150 time steps simulation

5. FUTURE PROSPECTS

5.1 Necessary improvements

Some substantial though quite straightforward improvement of the model will be achieved through the analysis of data collected from 3 one hectare permanent plots started 3 years ago. These data include DBH increment and Crown indices. Tree height and crown extension can easily and usefully be added to this set of measurement during the next campaign. The high sensitivity to crown shape claims special attention. Potential growth curves of height and of crown volume also need sound estimates. This will be achieved through the study of the morphology of existing trees of different development stage grown in favorable conditions. Measured variables will include: total height, crown projection on the floor approximated by an octagon, height of maximum crown width, and DBH. Taken as a body, these measures should allow to monitor the progressive change in shape which occurs in many species with aging : the slow loss of apical control by the main shoot (shapes becomes more excurrent) and the natural pruning of the lower branches.

Another major thrust of our future work should be the incorporation of the farmers management practices and their ecological knowledge into the model. This objective may be attained through sample surveys.

5.2 Validation

The main hypothesis made in the model concerning the functioning of the forest is the prevailing importance of light. Indeed light is assigned a crucial role in orienting the global dynamic through the crown position index which has an influence on recruitment, growth and mortality all at the time.

To what extent is the Crown Position index implemented in the model, a good indicator of the amount of light perceived by a tree ? This question may be addressed by adding a module to simulate the radiation transmission through the canopy and calculate the amount of light available to each tree. This module may be calibrated and validated independently from the growth model itself by using hemispherical photographs. This first step validation process might as well lead to a reconsideration of the geometrical representation of the tree (the symmetrical shape of a crown may appear to be too strong a constraint to get a reasonable estimate of light availability through the canopy). The second validation step will involve the growth model itself and could make use of one or two plots not used during the calibration step.

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Watershed protection research and upland – lowland connections: resolving conflicts

Meine van Noordwijk and Hubert de Foresta

ICRAF's interest in 'watershed issues' is based on:

1. After two decades of ICRAF research on plot-and farm level performance of agroforestry practices, and a first approach to the global environmental values in the ASB project, the intermediate 'regional' level relations between land use decisions and natural resource management issues have been identified as a gap; national and local policy decisions are probably strongly influenced by these types of relations, more so than by global concerns,
2. 'Watershed protection' is the raison d'etre for the 'protection forests' of the Indonesian state forest classification, with strong restrictions on local use of such forest lands. Especially in densely populated areas with a large inmigration *like in the Lampung Province* these protection forests are a major zone of conflict; in the past decades large numbers of people were evicted from protection forests and re-settled under the TRANSLOK program – at considerable economic and social costs and with limited success. According to data from the Department of Forestry the number of people in the protection forests has not decreased). Assessment of the types of local land use which could meet the aims of watershed protection may lead to the conclusions that certain forms of local land use can be accepted and can in fact be a much more cost effective way of achieving the government's objectives in maintaining a steady flow of water with low sediment content into the reservoirs used for irrigation and for generating electricity.
3. After the success with obtaining government recognition for local management of forest **resources through agroforestry** in Krui, where strong local community institutions still exist and can play a role in balancing farmers private interests with community and government objectives, extrapolation to other situations forms the next challenge: a setting with less clear local institutions, more migration and stronger down-stream interests forms a significant test of the validity of opportunities and limits of community-based natural resource management.
4. On the biophysical side, ICRAF's interest in scaling up from plot to field to farm and landscape level has led to a recognition of the importance of 'lateral resource flows' and 'lateral resource capture'. Surface phenomena, such as water and sediment run-off/runon and erosion/sedimentation depend on local spatial context and interactions, much more than 'vertical' processes such as groundwater recharge; for surface phenomena it is probably more important to know **where** trees are than to know **how many** there are. For water and sediment flows ***'filters'*** may form the relevant concept. A tentative landscape classification scheme for 'filters' (Fig. 1) is available for testing and quantification. Scaling up on the basis of 'sources' and 'filters' at a range of scales may be a significant step forward from most current approaches which are founded on GIS–based stratified sampling approaches (multiplying areas under a certain land use category with a typical value for that category, ignoring neighbourhood and border effects).
5. Initial model calculations (Fig.2) by ICRAF scientists show that the position of trees can indeed be of major importance. Whereas most of upland land use is in a 'mosaic' setting, most experimental studies have gone for 'pure' land use patterns; the real challenge is to work on methods which do justice to the interactions in mosaics and yet are practical enough to be applied.

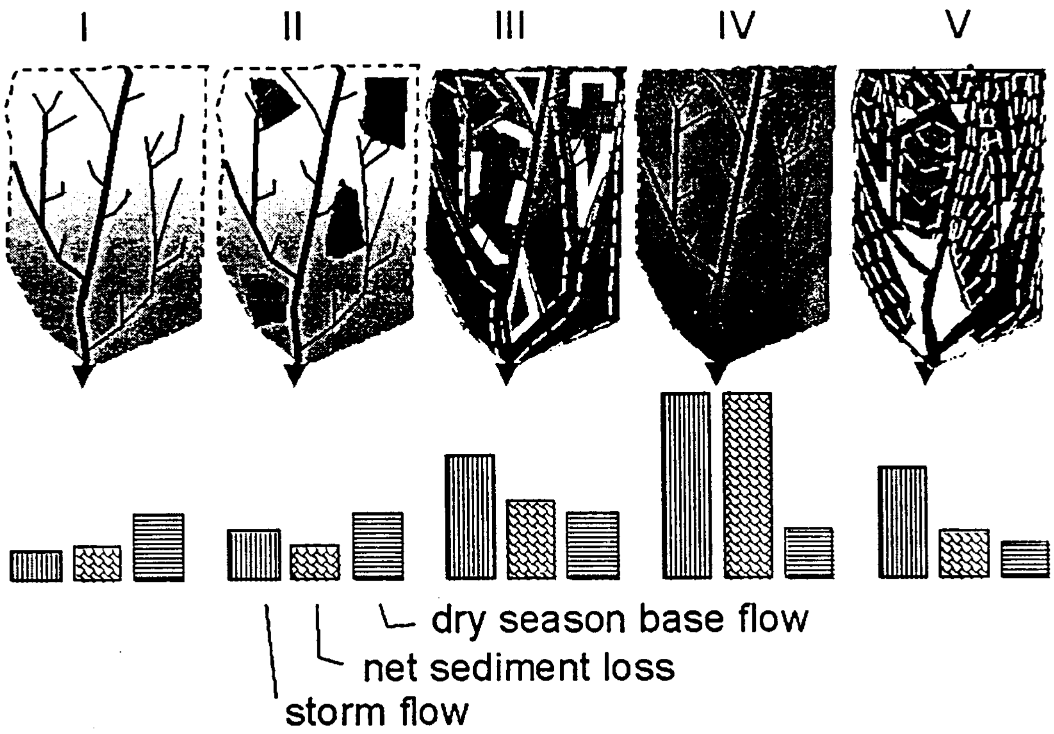

Figure 1. Schematic development of the landscape in a sub-watershed and its effects on storm flow, net sediment loss and dry-season base flow: I. original forest cover, II. patches of forest opened for shifting cultivation, III. intensification of land use has brought most land into cultivation, except for riverain borders and hedges along paths, IV. reclamation of all 'wastelands' has removed all filter strips causing a disproportional rise in net sediment loss, V. restored agroforestry landscape with permanently vegetated contour strips and riparian woodlands.(Van Noordwijk *et al.*,1998, *in press*)

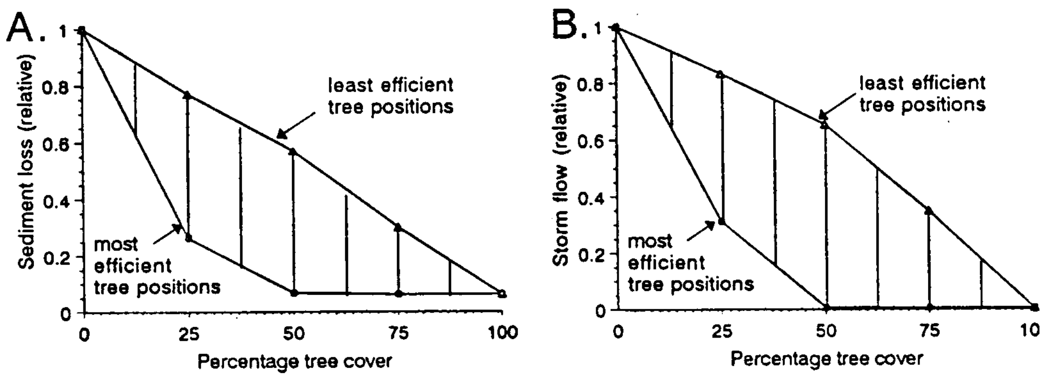

Figure 2. Model calculations of the effect of tree cover on sediment loss (*A*) and storm flow (*B*) for different tree configurations on the Machakos experimental station (Kenya); the 'least efficient' configurations had all trees in the upper part of the plot, the most efficient ones had all trees as filter before the outflow (Van Noordwijk *et al.*, in press)

6. Watershed-level work should emphasize interactions between upland and downstream areas. Such interactions exist at many levels:

- water is flowing from high to low, so land use in the source area affects downstream conditions more than vice-versa; traditionally river banks are favoured agricultural lands, by the combination of soil fertility and easy transport; modified river flow regimes (peak as well as base flow) have an effect on this type of land use; more modern sectors, such as irrigation-based agriculture in the lowland peneplain depends on reservoirs and/or constant river flow from the uplands,
- major towns and trading centres, and thus centres of political power are traditionally located at the mouth of rivers, giving a dominantly 'downstream' perspective on policies; towns are the main beneficiaries of electricity generated from dams and reservoirs in the uplands and are directly concerned with the life expectancy of such reservoirs.
- people can obtain their livelihoods both in uplands and in lowland peneplains; they can migrate into foothills and mountains when conditions there appear to be more attractive than elsewhere, or (at least at household level) depend on resources in both landscapes.

On the basis of such relations, institutions and mechanisms are needed to ensure that the different interests are addressed and that open conflict can be avoided or at least kept at manageable levels.

Past 'watershed projects' were often built on the rather naïve assumption that soil and water conservation would be in everybody's interest and that thus everybody would or should carry part of the costs required for a common benefit. The new perspective on sources and filters, on losers and beneficiaries, can well coincide with a renewed search for adequate institutions and regulations linking local and regional benefits.

In selecting research sites for ICRAF's research on watershed interactions and watershed relations we may thus look for sites which meet the following criteria:

I. Upper watershed areas classified as 'protection forest', but with considerable human 'encroachment' or settlements; evidence of human links between upper and middle watershed zones.
II. Middle watershed areas which allow study of traditional linkages (river margin agriculture) as well as modern sectors in irrigation schemes and resettlement projects.
III. Issues of irrigation , electricity reservoir protection, and/or coastal fisheries downstream.
IV. Provide a 'typical' landscape ecological transect through Sumatra, with reasonably fertile foothills and acid soil peneplain, so that extrapolation to other watersheds may be feasible.
V. Can form a basis for experiments with policy reform by local government institutions.
VI. Represent both 'traditional' community institutions and their interaction with migrants and a 'modern' sector.
VII. Complement ICRAF research sites elsewhere in S.E. Asia
VIII. Build on on-going activities and research by partner institutions and ICRAF,

In view of these criteria and building on the Characterization and Diagnosis work of the ASB program the suggestion was made to compare a watershed in Jambi (fairly low population density, dominated by rubber agroforests as major land use along the rivers, at least up till recent advance of oil palm plantations) with one in Lampung, with similar biophysical zonation but much higher population density.

In Lampung ICRAF and partners are working in Krui (West Lampung) and in Pakuan Ratu (North Lampung, ASB benchmark area). Halfway between these sites is the Sumber Jaya area, on the main access road to West Lampung, with major issues about human settlement in 'protection forests' and a recently developed reservoir for electricity generation; at close reach is the reservoir for the Way Rarem irrigation scheme. Around Sumber Jaya a considerable inmigration of people from the peneplain and from Java has transformed much of the previous forests into coffee gardens, often without soil cover and with dramatic erosion from the hills. In part of the valleys ricefields have developed as 'filter' ecosystem, benefitting from the fertility transfers. A research site operated by Lampung University with Japanese cooperators has started quantifying runoff and erosion for different types of coffee intercropping systems, and has made a first analysis of recent changes in land use (see p. 57)

The Sumber Jaya area appears to meet all our criteria for an upper watershed site. Sumber Jaya itself is part of the Tulang Bawang river system, in which the ASB North Lampung benchmark area has provided evidence for traditional river based land use as well as human migration links (both voluntarily and enforced). The BMSF (Biological Management of Soil Fertlity) site of Brawijaya University is located on the edge of the benchmark and has provided logistical support in the past. The lower reaches of the Tulang Bawang river are part of the newly established Kabupaten Manggala, where the new road to Palembang (Lintas Timur) has opened up the area for new settlement and agribusiness projects in the peat swamp forest zone. Manggala historically was the main town of Lampung, as it controlled access to the biggest river in Lampung (Tulang Bawang) and to the trade in pepper and coffee produced in the foothills around Kotabumi. Manggala declined in importance since the turn of the century and has been overshadowed by Bandar Lampung, closer to Java. As transmigration and the development of irrigation schemes for rice production have completely transformed Southern and Middle Lampung , North Lampung remained a 'frontier' until some twenty years ago. The development of the Lintas Timur has created new economic opportunities for Manggala . Lampung university operates a research site in Gunung Batin near the Gunung Madu sugarcane plantation, close to Manggala.

The Pakuan Ratu district, in North Lampung in which the ASB benchmark is located is the poorest part of Lampung (with the highest share of villages receiving poverty alleviation funds from the government) and allows us to study the interaction between local villages, spontaneous migrants, government resettlement projects (Translok) and agribusiness schemes.

In the Lampung province, the National Watershed Prioritization program has identified the Way Sekampung and Way Seputih watersheds as 'priority watersheds'. The adminstrative 'watersheds' (DAS), however, include more than one river system. The 'Way Seputih' DAS includes the Tulang Bawang watershed. The source areas of the Way Sekampung, Way Seputih and Tulang Bawang are close together on the East side of the Bukit Barisan mountain range. The Way Sekampung river is the lifeline of irrigation schemes in S. Lampung, as the Way Seputih is for those in C. Lampung. Compared to the Tulang Bawang river the middle and lower sections of these rivers are much less typical of the rest of Sumatra. Work on the source areas of the three river systems could be done using Sumber Jaya as a basis; in as far as we want to follow a single river system, the Tulang Bawang appears to be the most logical choice.

Steps to be taken now:

- ***explore how a focus on the Sumber Jaya area could meet our objectives,***
- ***establish partnerships with partners with similar interests (compare 'call for proposals' in the Philipines***

Appendix 1. Quantifying 'filter' functions for erosion management in landscape mosaics

1. Inventory potential filter elements in the landscape (e.g. vegetated strips around fields, stone rows, vegetated riparian strips, hedgerows along roads, rice paddies and other marsh vegetation), erosion hot-spots (e.g. interruptions in filters by footpaths) and design a relevant legend for a 'filter map'; this first step should be done in cooperation between researchers and local participants

2. Map filters and hot spots, superimposing them on maps of land units

3. Quantify the potential effectiveness (absorption capacity) of filters during single rain events and their regeneration between events

4. Quantify the overall filter function in the landscape by substraction:

Net sediment loss = Total net soil loss from all fields - All filter effects

Overall net sediment loss can be measured at the outflow of a stream from the micro catchment, while the total net soil loss from all fields can be obtained by adding estimates based on the USLE (or one of its modifications)

5. Design a spatially explicit model of the landscape topography with all land units and filter elements, and evaluate it for net soil loss for site specific rainfall data

6. Compare the results of 4 and 5 and re-iterate to steps 2, 3 and 5 if there are substantial gaps in the sediment book keeping

7. Evaluate the various filter elements from the farmers perspective: which ones represent direct value, which ones have indirect value by protecting vulnerable other landscape elements

8. On the basis of 1 - 7 answer the question whether there are enough filter elements in this landscape, what type and where other filter elements could be added by whom, at what cost and at what benefit (to whom?)

Alternatives To Slash-and-Burn (ASB)
ASB-Philippines Consortium

CALL FOR RESEARCH PROPOSALS

Funded by a grant from the Asian Development Bank

Analysis of Watershed Functions

The SE Asian Regional Programme of the International Centre for Research in Agroforestry (ICRAF), with funding from the Asian Development Bank (ADB), plans a major thrust in quantitative analysis of policy problems at the landscape scale, including the watershed-scale problems described below. This work is part of the global Alternatives to Slash-and-Burn (ASB) programme, which conducts research on sustainable upland systems as alternatives to unsustainable slash-and-burn in various parts of the tropics, including 3 major watershed research sites in SE Asia: the Manupali watershed on Mindanao in the Philippines, the Mae Chaem watershed in Northern Thailand, and the Tulang Bawang watershed in Lampung on Sumatra in Indonesia.

Framework for Analysis

Deforestation can be regarded as the loss of 'forest functions' as natural forests are replaced by other land use systems. National and regional concern for forest conservation and reforestation most often focuses on the loss of the watershed functions of natural forests. While some land uses may be as good as natural forest in this regard, land use systems differ significantly in their ability to supply these watershed functions.

Loss of watershed functions can be a combination of:
A. on-site loss of land productivity as a result of erosion,
B. off-site concerns about water quantity:
    B1. annual water yield,
    B2. peak (storm) flow,
    B3. dry season base flow
    B4. groundwater recharge or depletion,
C. off-site concerns about water quality, including siltation of reservoirs.

A is primarily an issue for upland farmers, whereas B and C are mainly the concerns of downstream interest groups who may be affected adversely as natural forest is converted into agricultural land uses.

Strategy for Watershed Research

Although past research and existing models allow a fair prediction of the soil and water balance at the plot-level under different land uses, they do not apply to landscape mosaics found in the real world. For sediment loads of rivers, for example, the location of trees may be more important than the area covered by trees, as riparian strips can intercept substantial sediment from erosion further up the slope. Moreover, in landscapes with an abundance of vegetated field border strips and hedgerows along paths, the link between on-site and off-site effects can be easily overstated.

Even with the most erosive field practices, contributions to sediment load in rivers probably depend more on 'hot spots' (foot paths, breakthroughs and landslides, roadsides, and construction sites). Indeed, there appears to be a major gap in the literature between plot/patch level studies and studies based on stream flow. The whole matrix of field borders in which the plots are set appears to have been ignored in most previous work.

In the *first phase* of this research, emphasis will go to development and validation of methods to measure sediment transfers across key scale changes in the sequence of steps from soil loss on site (called A above) to sedimentation at the watershed level (called C above). The starting point for this work will be the measurement of sediment transfer across various types of field boundaries and for various classes of landscape 'hotspots'. The *working hypothesis* is that transfer beyond field boundaries is small, regardless of land use, despite significant soil loss within fields for some types of land use. If the hypothesis is not rejected, this line of research is largely complete.

The second phase of the research will address the water quantity concerns (B above) corresponding to major policy problems: overall water supply (B1), flooding (B2), and seasonal water scarcity (B3). These represent some of the major natural resource management concerns for policymakers (at least in Southeast Asia), but building the database necessary to address them will require a longer period of research. (Recharge or depletion of aquifers (B4) is beyond the scope of present research plans.)

Proposals for the 1st Phase in the Philippines

The ASB-Philippines Consortium, coordinated by the Philippine Council for Agriculture, Forestry, and Natural Resources Research and Development (PCARRD), is seeking proposals for the *first phase* of ASB research on watershed functions in the Manupali watershed in Mindanao. Proposals should focus on measurement of sediment transfer across field boundaries and should test the working hypothesis stated above. Comprehensive proposals are sought for:

- development and testing of cost-effective methods for measurement of sediment transfer across field boundaries,
- development and testing of a descriptive system and techniques for mapping landscapes on the basis of the presence of 'filter' strips between cropped fields and the 'hotspots' of sediment loss at the landscape scale,
- measurement of water flow and sediment loads to calibrate and validate the descriptive system,
- analysis of data on water flow and sediment load to identify characteristic patterns of sediment loss and link these to the descriptive system for the landscape.

Deliverables / time frame

- Review (in English) of available secondary data sources submitted by [deadlinefor prelim report]
- Research report (in English) submitted by [deadline for final report].

Proposal preparation. Proposals must be written in English and must indicate the precise location and scope of the proposed research on watershed functions. Proposals also must include:

- a clear statement of research objectives and hypotheses to be tested
- discussion of available secondary data and methods of data collection
- discussion of methods to be used to analyze data and test hypotheses
- workplan, including level of effort (time commitment) of each team member

- a proposed budget, ***not to exceed 600,000 pesos***
- *curriculum vitae* for each member of the research team

Deadline for submission. To assure consideration, proposals should be submitted no later than [>>deadline for submission<<]. A committee of the ASB-Philippines Consortium will review the proposals for fit with ASB-Philippines objectives, scientific quality, and prospects for success. Announcement of selection of the successful proposal for research funding will be made by [deadline for announcement of award].

Send proposals to: Dr Dino Foronda, Director, Forestry and Environment Division, Philippine Council for Agriculture, Forestry, and Natural Resources Research and Development (PCARRD), Paseo de Valmayor, Los Banos, Laguna, Philippines 4030

For additional information, we encourage you to contact:
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Living on the Edge:
Evaluating options for people and ecosystems at the forest edge

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Abstract

Policy issues are central to natural resource management, but our knowledge of the efficacy of various policy initiatives is inadequate. It is not easy to devise policy frameworks and management systems that stimulate good land use, especially in the tropics where the issues are many and complex. Good intentions are not enough to secure good results, and too many policies have bad side effects. Unfortunately, the social and ecological consequences of policies and other initiatives are not always obvious, and there are few formal systems to offer reliable guidance. A decision support system could enable policy makers and planners to explore alternatives, and alert them to possible side-effects. This should facilitate better land use and thus help to conserve biodiversity and alleviate rural poverty.

Land use patterns are amenable to modeling. Most individuals behave rationally, and tend to maximize benefits and minimize risks to themselves and their families. Thus it should be possible to predict land use intentions using conventional utility functions. This is the basis for FLORES, the Forest-Land Oriented Resource Envisioning System, an ecosystem model of land use in forested landscapes. FLORES tessellates the landscape into relatively homogeneous tiles of various sizes and shapes, and simulates the growth of the vegetation and other environmental changes on each tile. It also models human interventions such as felling trees, clearing land, and planting crops. Even though our primary interest may be the trees and forests, it is essential to include the people and non-forest lands in the model, because without them, we cannot gain a complete understanding of the forces acting on the forest. FLORES links models of land use decisions in rural communities with models of crop growth, forest growth models, and ecosystem models to create a decision support system that allows alternatives to be investigated. Much of this work is not new research, rather it involves linking existing systems, building on existing knowledge, and making information available in a way that can be used. What is new is the way that concepts from ecology, economics and social science are integrated and applied.

The compilation of this model requires us to express existing knowledge completely, concisely, explicitly and unambiguously. Thus it enforces a rigorous synthesis of the state-of-the-art, and will help to identify gaps and inconsistencies in existing knowledge and prevailing paradigms. Perhaps the real strength of such a formal, spatially explicit model is that it allows strong empirical tests of propositions and assumptions in the model. These tests will enable us to verify our knowledge, to refute inconsistencies and strengthen inadequacies.

FLORES is implemented in AME, a graphical modeling interface for Prolog, the "programmed logic" language. The graphical interface makes the model accessible to researchers who are not fluent in computer programming, while allowing "hardened hackers" access to the underlying Prolog code. Thus AME offers a powerful and flexible platform that does not exclude less computer-literate participants in the project. The AME implementation allows decision-making to be modeled heuristically, so that benefit-maximizing objectives can be constrained by social obligations not readily represented in the more conventional linear programming formulations.

The present version of FLORES is an elementary prototype, but it provides the basis for iterative refinement and further development. Successive iterations of proposing, testing, refuting and reformulating or refining should contribute to our understanding, and eventually to a useful decision support system. Thus, in the short-term, FLORES provides a research framework, to foster collaboration, to synthesize knowledge in an explicit and usable way, to help identify gaps in existing knowledge, and to add rigor to research. Because it is spatially explicit, strong empirical tests of propositions and assumptions expressed in the model are possible.

In the longer term, it is intended to make FLORES available to policy-makers, advocates and others, to allow them to explore options and better understand consequences of their proposals. It should enable them to take initiatives with confidence, aware of any possible side-effects, and secure in the knowledge that alternatives have been examined and found to be inferior. Thus equipped, the key players in decision making should be able to satisfy personal and corporate goals while minimizing any detrimental environmental and social impacts.

The key product for such audiences may be the interface to geographic information systems, and the ability to create dynamic maps that show, movie-like, how land use responds over time to changes in policies and other instruments. One important use will be to identify areas where small changes in inputs give rise to large changes in predicted land uses. We need to know where these areas are, what parameters trigger shifts in dominant land use, and how these shifts occur. Any degradation or deforestation of forested lands due to changes in transport costs or commodity prices is of special interest.

It is not enough to equip the key influencers, advocates and their advisors. If wise land use is to be sustained, we must educate civil society. Thus we propose to package FLORES as an educational game similar to SimCity, and make it available to schools and interested public. Like the Maxis Corporation that produces SimCity, we will provide a simulator with options to influence the future, and with indicators of performance (e.g., biodiversity, rural poverty). We envisage that a user group will develop to provide diverse case studies, just as with SimCity. Ultimately, this educational role may be the most important aspect of FLORES, and our best way to attain a sustainable future.

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Land Use and Cover Changes in a Hilly Area of South Sumatra, Indonesia (from 1970 to 1990)

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We monitored the land use changes in a hilly area of West Lampung, South Sumatra, Indonesia, from 1970 to 1990. The main data sources were the land use maps produced in 1970, 1978, 1984, and 1990 covering on area of 27 km^2. The area was divided into 108×108 cell squares (0.25 km×0.25 km) and the largest land use form in the respective squares were mapped using a computer program. Fifty-seven percent of the study site was covered with primary forests in 1970, against 13% in 1990. Areas under plantation which were not recorded in 1970, increased to 60% in 1990. In addition, the change from monoculture plantations (mostly coffee plantation) to mixed plantations was noticeable from 1984 to 1990. Total upland area including upland area under shifting cultivation and upland fields with crops and vegetables only with fruit trees decreased from 21% in 1970 to 0.1% in 1990, clearly suggesting the establishment of plantation agriculture, mainly coffee plantations, in the hilly areas, and the transfer of areas for crop and vegetable production to the middle terraces in Lampung Province. In large areas land-use had changed from some forms to others at intervals of 6–8 y in the study site. Transmigration and resultant impact of increasing population were the major driving forces in land use changes.

Key Words: **forest, grassland, plantation, shifting cultivation, transmigration.**

The annual income *per capita* in Indonesia was 670$ in 1992, and it was the lowest among the four ASEAN countries (Indonesia, Malaysia, Philippines, and Thailand). However the mean real annual growth rate was 4.5% in Indonesia between 1965 and 1990, which was comparable to that in Thailand (4.4%). The real annual growth rate of the economy in Indonesia was 7.2% between 1970 and 1980, and 5.7% between 1980 and 1992, respectively. In Lampung Province, South Sumatra, the average annual economic growth rate during the period from 1969 to 1988 was 8.8%, and in 1994, 7.1% (Pemda TK-I Lampung 1992; Kantor Pusat Statistik Propinsi Lampung 1996). These figures were consistently higher than those of the national average.

In contrast to the economic growth rate, however, the income *per capita* in Lampung Province has been lower than the national average. In 1983, the income *per capita* in Lampung was only 371$ (Kantor Pusat Statistik Propinsi Lampung 1996), almost half of the national income *per capita*. The lower income in Lampung was related to the higher population growth particularly in the period before 1980, which in turn, indirectly affected the land use changes. In 1930, the population density in Lampung Province which was 376,000, increased to 1,472,000 in 1961, 2,456,000 in 1971, 4,155,000 in 1980, and 5,318,000 in 1990 (Pemda TK-I Lampung 1992). During these periods, the population growth in Lampung Province remained higher than the national average.

The total GDP of Indonesia increased rapidly: 8.4 billion US$ (b$) in 1970, 62 b$ in 1980, and 96 b$ in 1990. Due to the drastic development of the mining industry, manufacturing industry and commerce sectors. The contribution percentages of the agricultural sector to the total GDP in Indonesia decreased from 47.2% in 1970 through 24.8% in 1980 to 17.6% in 1993 (Asian Development Bank 1970-1992).

The aim of this paper is to monitor the land use changes in the study site located in hilly areas in West Lampung, Lampung Province, in the past 20 y from 1970 to 1990, considering the national policy, transmigration, and the agro-economical circumstances. We were able to examine the land use changes in the study site in close relation with the national policy by analyzing land use maps and several statistics in Indonesia. This report is the first in a report series under the Project entitled "Basic Researches on Developing Techniques for Sustainable Biological Production in the Regions of Red Acid Soils" supported by Ministry of Education, Science, Sports and Culture of Japan. In the following papers, the effects of land use change on soil fertility will be reported in terms of soil chemistry, soil microbiology, and soil enzymology.

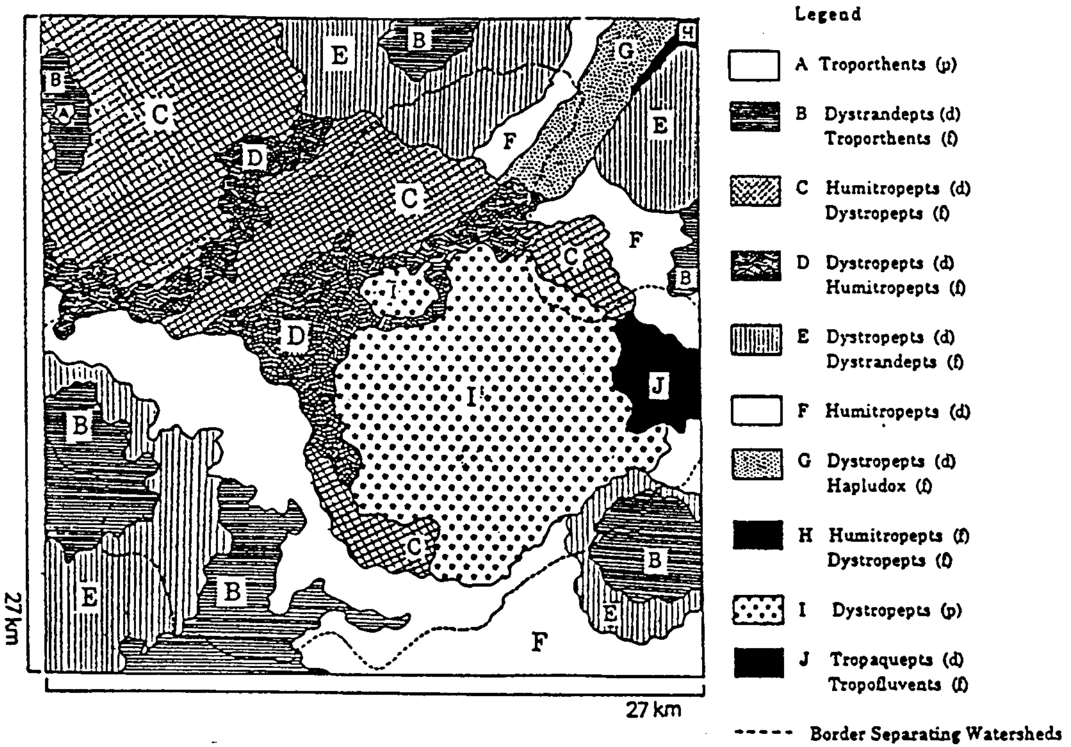

Fig. 1. Soil map of the study site. p, d, and f in parentheses indicate the soil area proportions. p: predominant (>75%), d: dominant (50-75%), f: fair (25-50%).

MATERIALS AND METHODS

Location of study site. The study site which was located at 4°55′S to 5°10′S and 104°19′E to 104°34′E, in West Lampung, Lampung Province, South Sumatra, covers an area of 27 km². This site was located in the hilly area surrounding a watershed (Fig. 2). The elevation of the study site ranges from 780 to 1,700 m above sea level. The areas separating watersheds were mountainous. In addition, there was a mountain (1,623 m) in central part of the study area. Villages were generally located at the low and flat areas. The distribution of major soil groups in the study site is shown in Fig. 1 (Center for Soil and Agroclimate Research 1989・1991).

Data sources of land use information. The main data sources were the land use maps of the area produced in 1970, 1978, 1984, and 1990 and published by Kantor Agraria (now BDN) (Table 1). The maps were patterned according to the land use form. They contained fairly detailed information on the land use form; kind of trees in forest land, kind of crops and number of harvests in agricultural land, etc. We only used the information on land use form.

Data processing (method of mapping). The study site consists of 9 maps; 9 km × 9 km in size designated 1-1 to 3-3 (Fig. 3), however due to the absence of 3 maps covering the upper grids, only 6 grids 1-2 to 3-3 were available in 1970. We prepared the data files

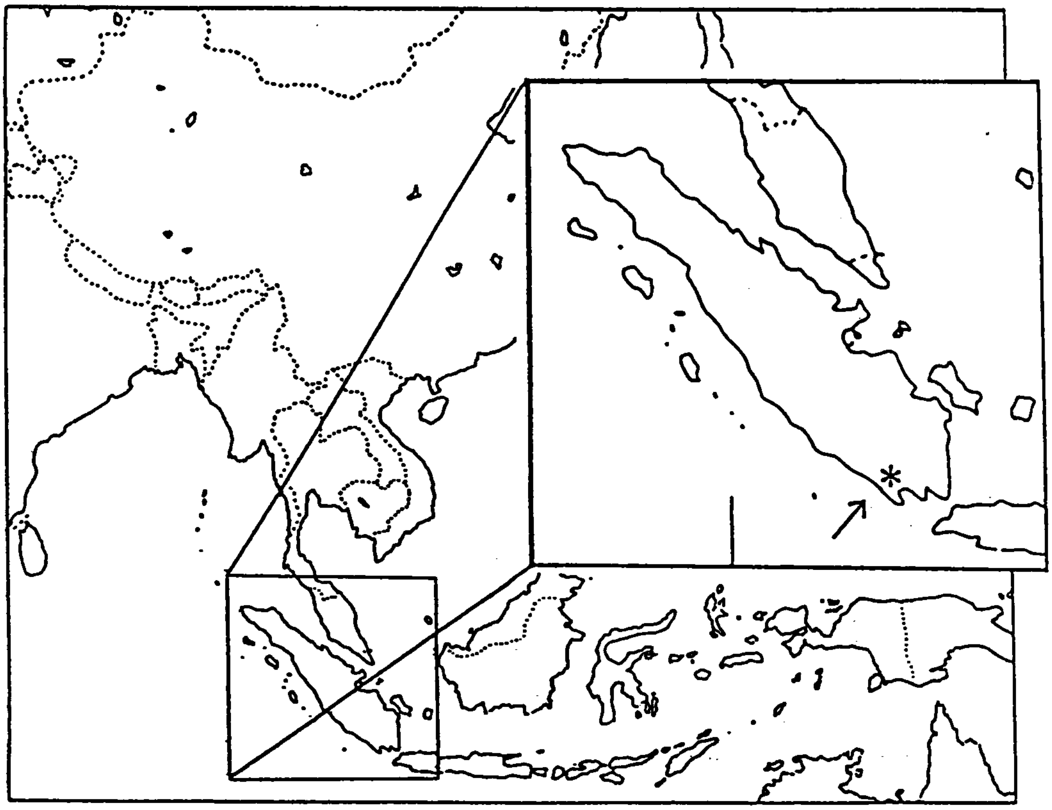
Fig. 2. Location of study site.

Table 1. List of data sources for land use mapping.

Year	Scale	Location	Sources	Mapping	Printing
1970	1 : 100,000	104°20′-105°20′E 4°40′-5°40′ S	Land use map (Kantor Agraria)	May, 1970	September, 1970
1978	1 : 25,000	104°19′-104°34′E 4°55′-5°10′ S	Land use map (Kantor Agraria)	January, May, July, 1978	November, 1980; February, 1981; March, June, 1983
1984	1 : 25,000	104°19′-104°34′E 4°55′-5°10′ S	Revision of 1978 map (Kantor Agraria)	March, 1984	October, 1984; March, December, 1986
1990	1 : 25,000	104°19′-104°34′E 4°55′-5°10′ S	Revision of 1978 map and revision of 1984 map (Kantor Agraria)	October, November, 1990	November, 1991; August, 1992

Maps were prepared based on LandSat images and field surveys using topographic maps.

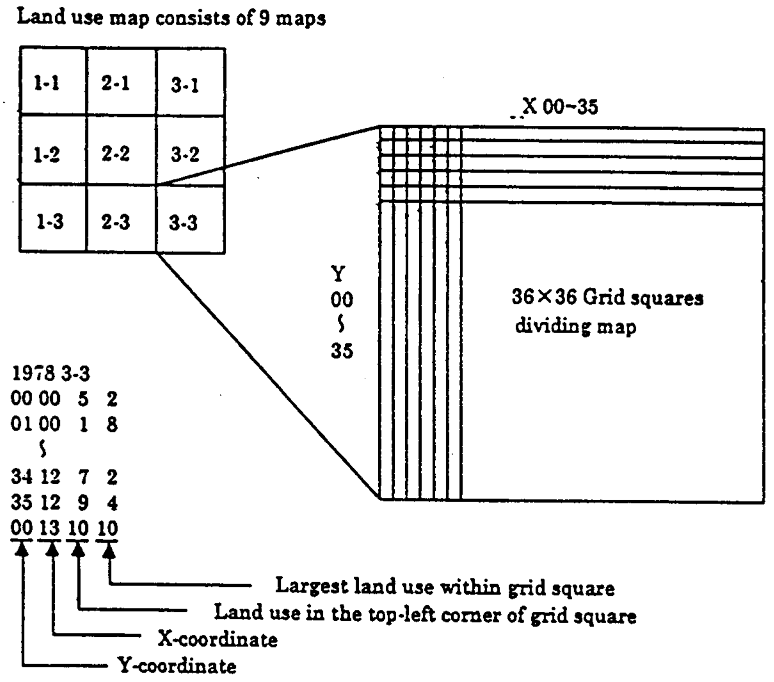

Fig. 3. Coordinate system of land use maps.

from each grid according to the following processes (Himiyama 1991);

1) Each grid was divided into 36×36 cell squares which covered an area of 0.25 km× 0.25 km, with coordinates as X(00~35) and Y(00~35).

2) The information on land use form in the map was coded to double figures, the land use form in the top-left corner of the respective cell squares and the largest land use form in the square. The land use form was classified into the following 11 different categories.

1: Residential areas, including villages, cemeteries, and playgrounds.

2: Paddy fields.

3: Upland fields (crops and vegetables).

4: Upland area under shifting cultivation.

5: Upland fields (mixed, crops and vegetables with fruit trees).

6: Plantation lands (monoculture, mostly coffee plantations).
7: Plantation lands (mixed).
8: Dense forests (mostly primary forests).
9: Underbrush forests (mostly secondary forests).
10: Ponds.
11: Grasslands (mostly alang alang (*Imperata cylindrica*)).

3) The codes of the land use form in the top-left corner for calculating the area of the respective land use forms, using the systematic point sampling method (Coleman and Catling 1982) and the largest land use in respective cell squares for drawing the land use map were stored as a text file using a personal computer with a wordprocessor software (Fig. 2).

4) The program to draw the land use map was run on Chipmunk-basic 3.1.0 (Copyright 1990, 1994 Ronald H. Nicholson, Jr.), BASIC interpreter.

RESULTS

As shown in Fig. 1, Dystropepts, Dystrandepts, and Troporthents (legends B and E) were distributed along the watershed areas, while Tropaquepts and Tropofluvents (legend J) were distributed in the lowland area in the right central part of the map.

Figure 4 shows the land use maps produced in 1970, 1978, 1984, and 1990. Tables 2 to 4 summarize the areas of respective land use forms and of land use change from some form to others. Due to the lack of information in the upper third part, total area considered in the map of 1970 covered 486 km², while in 1978, 1984, and 1990, 729 km² each. In addition, Figs. 5 and 6 sum up the areas of underbrush forests and grasslands, respectively, indicating to and from which form they were changed between 1978 and 1984 and between 1984 and 1990.

1970 (Fig. 4; Table 2)

Most of the area was occupied by dense forests, 57% (279 km²) of the total area (486 km²), followed by underbrush forests (12%), upland area under shifting cultivation (9.4%), and grasslands (9.0%). Underbrush forests and grasslands succeeded shifting cultivation areas —fallow areas—grasslands—secondary forests. The sum of upland areas in which crops and vegetables were grown with and without fruit trees accounted for 11.2% of the total, and paddy fields accounted for less than 1% of the total. There was no plantation area in 1970.

1978 (Fig. 4; Tables 2 and 3)

When the same area which was mapped in 1970 was observed, the area under dense forests and underbrush forests had decreased markedly from 57 to 44% and from 12 to 7.3% of the total area, respectively, while plantation areas, mainly coffee plantations appeared first in 1978 and occupied 18% of the total area (486 km²; Table 2). The area under paddy fields and grasslands also increased significantly. The distribution percentages of the respective land use forms varied when the upper third area (additional 243 km²) was included. Dense forests occupied 33% of the total area (729 km²), followed by plantation areas 22%, grasslands 18%, and underbrush forests 16% (Table 3).

More complicated and drastic land use changes were recognized when the changes of the respective land use forms from and to other forms were considered. For example as shown in Table 2, although the percentage of grasslands in the total area increased from 9.0% (44 km²) in 1970 to 18% (88 km²) in 1978, the area which was under grasslands both in 1970 and in 1978 accounted for only 4.4% (21 km²) and the remaining area, 13.8% (67 km²), of the

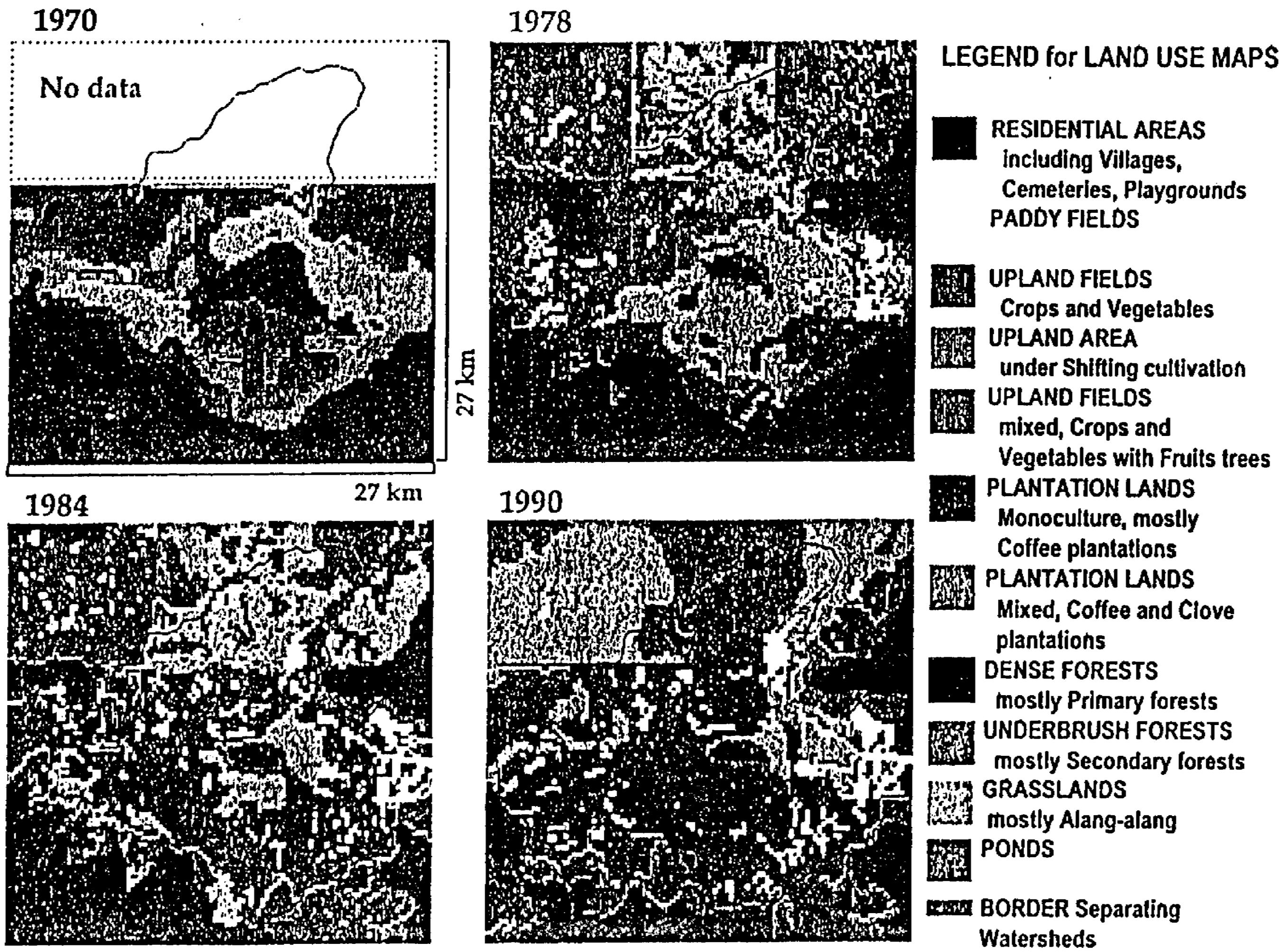

Fig. 4. Land use maps produced in 1970, 1978, 1984, and 1990.

Table 2. Land use forms in 1970 and 1978 and land use changes during 1970 and 1978.

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	LEGEND	RESIDENTIAL AREAS	(%)	PADDY FIELDS	(%)	UPLAND FIELDS	(%)	UPLAND AREA Shifting	(%)	UPLAND FIELD Mixed	(%)	PLANTATIONS Monoculture	(%)	PLANTATIONS Mixed	(%)	PLANTATIONS Total	(%)	FORESTS Dense	(%)	FORESTS Underbrush	(%)	PONDS	(%)	GRASS LANDS	(%)	Total 1978	(%)
1978	RESIDENTIAL AREAS	1.69	0.35	0.19	0.04	0.56	0.12	0.63	0.13	2.44	0.50	0.00	0.00	0.00	0.00	0.00	0.00	0.56	0.12	0.75	0.15	0.00	0.00	0.13	0.03	6.94	1.43
	PADDY FIELDS	0.94	0.19	0.38	0.08	2.19	0.45	5.25	1.08	3.31	0.68	0.00	0.00	0.00	0.00	0.00	0.00	2.69	0.55	0.88	0.18	0.00	0.00	1.06	0.22	16.69	3.43
	UPLAND FIELDS	0.31	0.06	0.06	0.01	0.81	0.17	1.00	0.21	0.81	0.17	0.00	0.00	0.00	0.00	0.00	0.00	6.31	1.30	3.00	0.62	0.00	0.00	3.75	0.77	16.06	3.31
	UPLAND AREA Shifting	0.00	0.00	0.06	0.01	3.75	0.77	5.00	1.03	1.06	0.22	0.00	0.00	0.00	0.00	0.00	0.00	7.31	1.50	0.38	0.08	0.00	0.00	6.13	1.26	23.69	4.87
	UPLAND FIELDS Mixed	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	PLANTATIONS Monoculture	1.06	0.22	0.50	0.10	12.19	2.51	14.75	3.00	13.56	2.79	0.00	0.00	0.00	0.00	0.00	0.00	21.19	4.36	9.56	1.97	0.00	0.00	6.00	1.23	78.81	16.22
	Mixed	0.00	0.00	0.00	0.00	0.88	0.18	0.81	0.17	0.94	0.19	0.00	0.00	0.00	0.00	0.00	0.00	1.50	0.31	2.63	0.54	0.00	0.00	0.06	0.01	6.81	1.40
	Total	1.06	0.22	0.50	0.10	13.06	2.69	15.56	3.20	14.50	2.98	0.00	0.00	0.00	0.00	0.00	0.00	22.69	4.67	12.19	2.51	0.00	0.00	6.06	1.25	85.63	17.62
	FORESTS Dense	0.00	0.00	0.00	0.00	0.13	0.03	2.81	0.58	0.56	0.12	0.00	0.00	0.00	0.00	0.00	0.00	203.06	41.78	6.56	1.35	0.00	0.00	0.00	0.00	213.13	43.85
	FORESTS Underbrush	0.00	0.00	0.00	0.00	0.13	0.03	3.00	0.62	0.13	0.03	0.00	0.00	0.00	0.00	0.00	0.00	15.00	3.09	11.88	2.44	0.00	0.00	5.25	1.08	35.38	7.28
	PONDS	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.19	0.04	0.00	0.00	0.00	0.00	0.00	0.00	0.19	0.04
	GRASSLANDS	0.06	0.01	0.56	0.12	5.06	1.04	12.31	2.53	5.94	1.22	0.00	0.00	0.00	0.00	0.00	0.00	21.06	4.33	22.13	4.55	0.00	0.00	21.19	4.36	88.31	18.17
	Total 1970	4.06	0.83	1.75	0.36	25.69	5.29	45.56	9.38	28.75	5.92	0.00	0.00	0.00	0.00	0.00	0.00	278.88	57.38	57.75	11.88	0.00	0.00	43.58	8.96	486.00	

	A	
B	X	Y

A → B; Xkm^2, Y%

Areas (Xkm^2, and Y% in $486km^2$) converted from Land use form A to Land use form B during 1970 and 1978.

Table 3. Land use forms in 1978 and 1984 and land use changes during 1978 and 1984.

		1978																									
	LEGEND	RESIDENTIAL AREAS	(%)	PADDY FIELDS	(%)	UPLAND FIELDS	(%)	UPLAND AREA Shifting	(%)	UPLAND FIELD Mixed	(%)	PLANTATIONS						FORESTS Dense	(%)	FORESTS Underbrush	(%)	PONDS	(%)	GRASS LANDS	(%)	Total 1984	(%)
												Monoculture	(%)	Mixed	(%)	Total	(%)										
1984	RESIDENTIAL AREAS	2.88	0.39	1.06	0.15	0.50	0.07	0.25	0.03	0.00	0.00	4.81	0.66	0.75	0.10	5.56	0.76	0.38	0.05	0.50	0.07	0.00	0.00	1.25	0.17	12.38	1.70
	PADDY FIELDS	1.06	0.15	12.19	1.67	1.13	0.15	4.44	0.61	0.00	0.00	7.69	1.05	0.56	0.08	8.25	1.13	0.19	0.03	2.88	0.39	0.00	0.00	6.50	0.89	36.63	5.02
	UPLAND FIELDS	0.00	0.00	0.19	0.03	0.19	0.03	0.69	0.09	0.00	0.00	1.50	0.21	0.00	0.00	1.50	0.21	0.25	0.03	0.88	0.12	0.00	0.00	4.13	0.57	7.81	1.07
	UPLAND AREA Shifting	0.00	0.00	0.00	0.00	0.31	0.04	0.00	0.00	0.00	0.00	0.44	0.06	0.00	0.00	0.44	0.06	1.13	0.15	0.06	0.01	0.00	0.00	0.44	0.06	2.38	0.33
	UPLAND FIELDS Mixed	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	PLANTATIONS Monoculture	3.25	0.45	6.81	0.93	10.13	1.39	23.38	3.21	0.00	0.00	119.38	16.38	5.31	0.73	124.69	17.10	40.56	5.56	39.63	5.44	0.00	0.00	56.06	7.69	304.50	41.77
	Mixed	0.25	0.03	0.25	0.03	0.25	0.03	0.13	0.02	0.00	0.00	2.63	0.36	0.00	0.00	2.63	0.36	0.19	0.03	0.38	0.05	0.00	0.00	2.88	0.39	6.94	0.95
	Total	3.50	0.48	7.06	0.97	10.38	1.42	23.50	3.22	0.00	0.00	122.00	16.74	5.31	0.73	127.31	17.46	40.75	5.59	40.00	5.49	0.00	0.00	58.94	8.08	311.44	42.72
	FORESTS Dense	0.00	0.00	0.06	0.01	0.06	0.01	0.00	0.00	0.00	0.00	0.81	0.11	0.06	0.01	0.88	0.12	151.25	20.75	2.56	0.35	0.13	0.02	1.00	0.14	155.94	21.39
	FORESTS Underbrush	0.06	0.01	0.63	0.09	1.38	0.19	2.94	0.40	0.00	0.00	4.63	0.63	0.13	0.02	4.75	0.65	33.63	4.61	26.56	3.64	0.00	0.00	8.69	1.19	78.63	10.79
	PONDS	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.06	0.01	0.00	0.00	0.06	0.01
	GRASSLANDS	0.00	0.00	0.13	0.02	2.13	0.29	3.25	0.45	0.00	0.00	10.00	1.37	0.00	0.00	10.00	1.37	10.13	1.39	44.63	6.12	0.00	0.00	53.50	7.34	123.75	16.98
	Total 1978	7.50	1.03	21.31	2.92	16.06	2.20	35.06	4.81	0.00	0.00	151.88	20.83	6.81	0.93	158.69	21.77	237.69	32.60	118.06	16.20	0.19	0.03	134.44	18.44	729.00	

	A	
B	X	Y

$A \rightarrow B; X\text{km}^2, Y\%$

Areas ($X\text{km}^2$, and Y% in 729km^2) converted from Land use form A to Land use form B during1978 and 1984.

Table 4. Land use forms in 1984 and 1990 and land use changes during 1984 and 1990.

		1984										PLANTATIONS															
	· LEGEND	RESIDENTIAL AREAS	(%)	PADDY FIELDS	(%)	UPLAND FIELDS	(%)	UPLAND AREA Shifting	(%)	UPLAND FIELD Mixed	(%)	Monoculture	(%)	Mixed	(%)	Total	(%)	FORESTS Dense	(%)	FORESTS Underbrush	(%)	PONDS	(%)	GRASS LANDS	(%)	Total 1990	(%)
1990	RESIDENTIAL AREAS	4.56	0.63	2.19	0.30	0.25	0.03	0.00	0.00	0.00	0.00	7.88	1.08	0.38	0.05	8.25	1.13	0.25	0.03	0.19	0.03	0.00	0.00	0.38	0.05	16.06	2.20
	PADDY FIELDS	1.25	0.17	20.31	2.79	0.44	0.06	0.00	0.00	0.00	0.00	13.94	1.91	0.38	0.05	14.31	1.96	0.13	0.02	0.69	0.09	0.00	0.00	1.88	0.26	39.00	5.35
	UPLAND FIELDS	0.00	0.00	0.00	0.00	0.31	0.04	0.06	0.01	0.00	0.00	0.44	0.06	0.00	0.00	0.44	0.06	0.00	0.00	0.06	0.01	0.00	0.00	0.00	0.00	0.88	0.12
	UPLAND AREA Shifting	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	UPLAND FIELDS Mixed	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	PLANTATIONS Monoculture	4.50	0.62	9.50	1.30	5.81	0.80	2.00	0.27	0.00	0.00	149.13	20.46	3.00	0.41	152.13	20.87	47.13	6.46	37.00	5.08	0.00	0.00	41.63	5.71	299.69	41.11
	Mixed	1.69	0.23	4.44	0.61	0.38	0.05	0.31	0.04	0.00	0.00	104.44	14.33	2.00	0.27	106.44	14.60	6.38	0.87	6.44	0.88	0.00	0.00	14.31	1.96	140.38	19.26
	Total	6.19	0.85	13.94	1.91	6.19	0.85	2.31	0.32	0.00	0.00	253.56	34.78	5.00	0.69	258.56	35.47	53.50	7.34	43.44	5.96	0.00	0.00	55.94	7.67	440.06	60.37
	FORESTS Dense	0.13	0.02	0.06	0.01	0.06	0.01	0.00	0.00	0.00	0.00	4.38	0.60	0.00	0.00	4.38	0.60	79.81	10.95	4.88	0.67	0.06	0.01	3.38	0.46	92.75	12.72
	FORESTS Underbrush	0.25	0.03	0.13	0.02	0.56	0.08	0.00	0.00	0.00	0.00	22.31	3.06	1.19	0.16	23.50	3.22	21.81	2.99	28.69	3.94	0.00	0.00	56.63	7.77	131.56	18.05
	PONDS	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.31	0.04	0.00	0.00	0.31	0.04	0.00	0.00	0.19	0.03	0.00	0.00	0.00	0.00	0.50	0.07
	GRASSLANDS	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.69	0.23	0.00	0.00	1.69	0.23	0.44	0.06	0.50	0.07	0.00	0.00	5.56	0.76	8.19	1.12
	Total 1984	12.38	1.70	36.63	5.02	7.81	1.07	2.38	0.33	0.00	0.00	304.50	41.77	6.94	0.95	311.44	42.72	155.94	21.39	78.63	10.79	0.06	0.01	123.75	16.98	729.00	

	A	
B	X	Y

A → B; Xkm^2, Y%

Areas (Xkm^2, and Y% in 729km^2) converted from Land use form A to Land use form B during1984 and 1990.

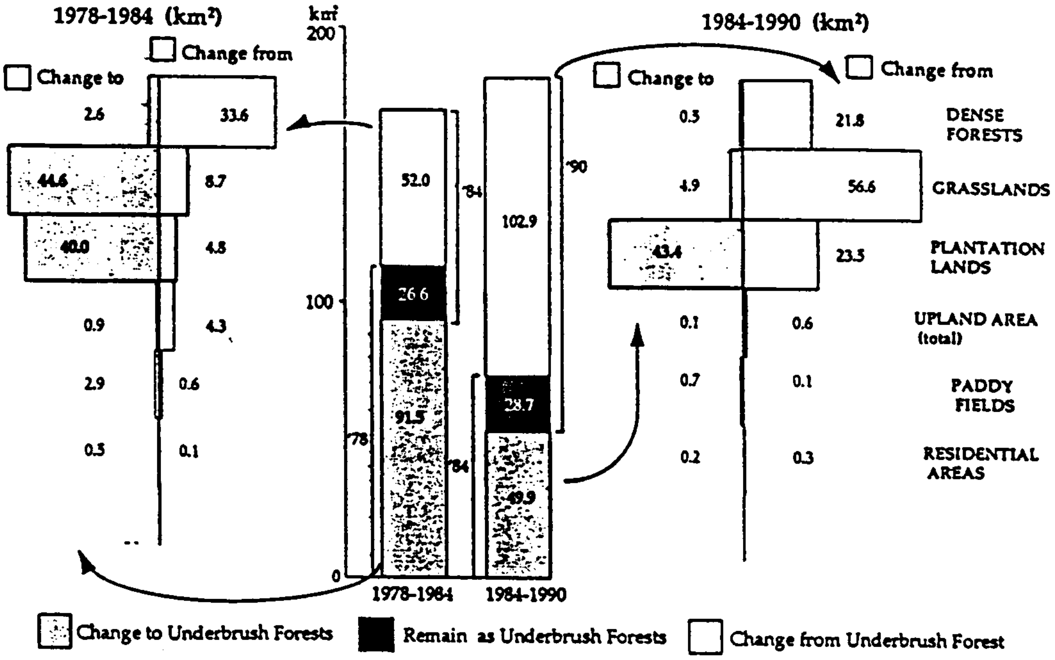

Fig. 5. Areas under underbrush forests (mostly secondary forests) indicating to and from which form they were changed during 1978 and 1984, and during 1984 and 1990.

grasslands was newly converted from underbrush forests (4.6%, 22 km^2), dense forests (4.3%, 21 km^2), and upland area under shifting cultivation (2.5%, 12 km^2). Total plantation area in 1978 was mainly derived from upland area under shifting cultivation (3.2%, 16 km^2), dense forests (4.7%, 23 km^2) and upland fields (for crops and vegetables and "mixed"; 5.7%, 28 km^2).

1984 (Figs. 4-6; Table 3)

Total plantation area doubled from 1978 to 1984, and became the largest land cover (43% of the total area), while the area under dense forests and underbrush forests decreased to nearly two-thirds of the area in 1978 to cover 21 and 11% of the total, respectively. Forty-three percent of grasslands (59 km^2), 17% of dense forests (41 km^2), 34% of underbrush forests (40 km^2), and 67% of upland area under shifting cultivation (24 km^2) were converted to land for plantation. Underbrush forests were converted to grasslands (6.1% of total; 45 km^2) and plantation areas (5.5%, 40 km^2). As for grasslands, 43% of them were converted to plantation areas, while 38% of the underbrush forests were converted to grasslands, which resulted in the apparent occupation of a similar percentage of grasslands in 1978 (18%) and 1984 (17%). Upland area under shifting cultivation also decreased significantly from 1978 (4.8%) to 1984 (0.3%), which was mainly due to the conversion to plantation lands. Area under paddy fields increased from 2.92% in 1978 to 5.02% in 1984 of the total study area.

1990 (Figs. 4-6; Table 4)

Areas for monoculture plantation, mostly coffee plantations, in 1990 were almost the same as those in 1984 covering 41% of the total area. However, nearly half of the areas under monoculture plantations in 1984 were converted to mixed plantations (104 km^2) and

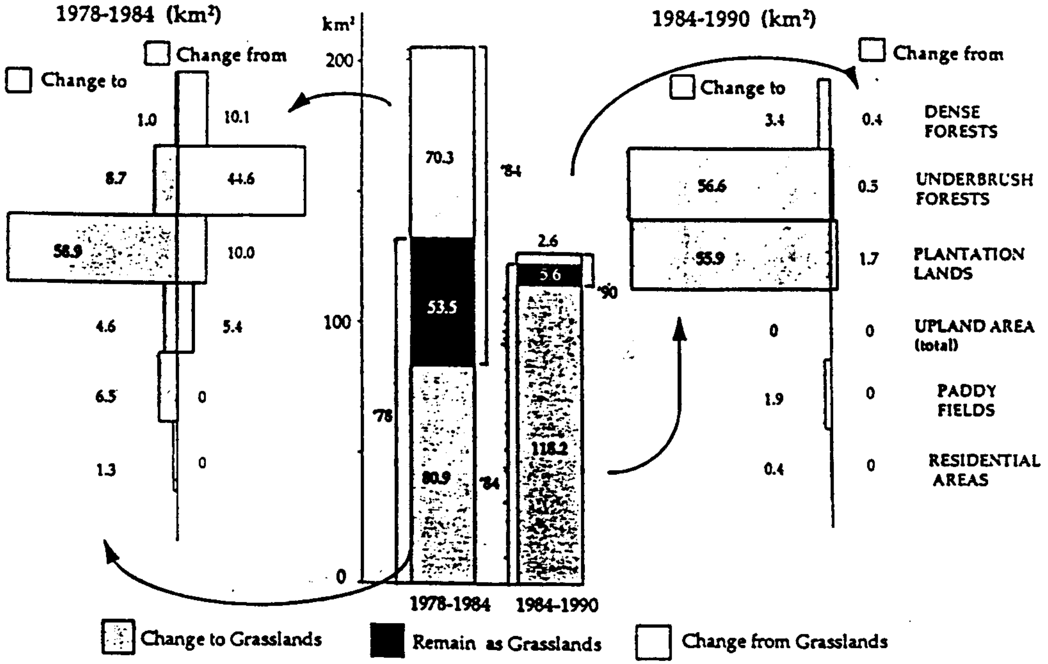

Fig. 6. Areas under grasslands indicating to and from which form they were changed during 1978 and 1984, and during 1984 and 1990.

underbrush forests (22 km²). On the other hand, 30% of dense forests (47 km²), 34% of grasslands (42 km²), and 47% of underbrush forests (37 km²) were converted to monoculture plantations, and these areas were larger than those converted to mixed plantations. Though the area for paddy fields increased only slightly from 36.6 km² in 1984 to 39.0 km² in 1990, 13.9 km² of the paddy field area in 1984 were converted to plantation areas and 14.3 km² of plantation areas in 1984 were converted to paddy fields in 1990. The area under dense forests decreased further during 1984 and 1990 mainly due to the conversion to plantation areas (7.3% of the total), while the area underbrush forests increased by 7% of the total area from grasslands (7.8%, 57 km²), and plantation areas (3.2%, 24 km²). The area under mixed plantations increased drastically between 1984 and 1990 and occupied 19% of the total area, mainly due to the change from monoculture plantations (14%, 104 km²). In addition, the area under grasslands decreased markedly from 17% in 1984 to 1.1% in 1990 changing to underbrush forests (7.8%) and plantation areas (7.7%).

Thus, Tables 2 to 4 and Figs. 5 and 6 show that the actual changes in land use form, both the increase and decrease of respective areas, were not simple in the study site. The conversion from some land use form to others was very rapid within a period of 6-8 y.

Based on the land use change between 1970 and 1990, it was generally recognized that the land use change started from the areas near villages and extended to the mountainous areas, the border separating watersheds (Fig. 4). A small area in the central part of the study site remained as dense forests, because the area was mountainous and designated as preservation forest. No significant relationships between the land use change and soil properties were observed in this area (Figs. 1 and 4).