# Causes and Effects of Land-Use Change in Central Rondônia, Brazil


## Abstract

*Land-use change is one of the major factors affecting global environmental conditions. Modeling land-use change requires combining spatially explicit ecological information with socioeconomic factors. A modeling system has been developed that integrates sub-models of human colonization and ecological interactions to estimate patterns and rates of deforestation under different immigration and land management scenarios. The simulation modeling system is being applied to the Brazilian state of Rondônia where deforestation has increased at a faster rate over the past two decades than anywhere else in the world. The model projections suggest that appropriate land management can both reduce carbon release and improve the length of time farmers are able to remain successfully on the land. The model provides a tool to evaluate the implications of various land management options. Analysis of field interviews with farmers from central Rondônia indicates that the model does represent much of the land-use dynamics as well as points out aspects of the system where the model needs improvements. Together, the model and data suggest that land-use changes in central Rondônia are a function of lot size, land-use history, initial soil and vegetation conditions, land-use choices (planting annual, perennial, or pasture), market conditions, and effects of illness on work.*


## Introduction

Changes in land use affect social, economic, and ecological conditions. The social effects include changes in standard of living, education and employment opportunities, and health conditions. In particular, deforestation frequently disrupts and may destroy the lifestyles of indigenous populations (Souza, 1980). The economic repercussions of land-use change include changes in family incomes and the price of goods, often as a function of altered transportation costs. For example, deforestation may cause an increase in the price of fuels such as wood and charcoal, as well as lead to a shortage of these fuels (Allen and Barnes, 1985). Land-use changes have multiple ecological impacts. The ecological effects of large scale forest loss include decreased biodiversity (Wilson, 1988), disruption of hydrological regimes (Shukla *et al.*, 1990), degradation of soil conditions (Buschbacher *et al.*, 1988), and changes in the balance of greenhouse gases in the atmosphere, which may in time induce climate change (Post *et al.*, 1990; Dale *et al.*, 1991).

Traditional methods for examining land-use change and its impacts have typically treated the socioeconomic and ecological effects independently. This separation is partly due to the historical independence of the fields of study and partly due to the difficulty of combining the analyses. However, it is important to consider these aspects of land-use change simultaneously, for they can affect each other. For example, land-use activities can instigate soil degradation which affects the economic value of the land and which, in turn, reduces the ability of the land to sustain a family.

To evaluate the wide range of causes and effects of land-use change, a simulation model has been developed that integrates the socioeconomic and ecologic components (Southworth *et al.*, 1991; Dale *et al.*, 1993a). The model is used to contrast typical patterns of land use in Rondônia, Brazil with a system of sustainable agriculture. Area cleared, carbon released, and time familes remain on a lot are used for the comparison. The purpose of this paper is to examine the socioeconomic causes of land-use changes in Rondônia by analyzing model components in conjunction with data collected from interviews with farmers in the region.

## Background

### Deforestation in Rondônia, Brazil

Rondônia, Brazil was chosen for this study because massive land-use change has occurred there in the last two decades (Malingreau and Tucker, 1988). Rondônia is located in the south central Amazon basin and comprises an area of 243,000 km². Colonization programs were begun in 1968 to meet four main objectives: (1) to establish people on the land, (2) to increase the standard of living, (3) to promote economic growth, and (4) to use the land's resources (Leite and Furley, 1985). There was also an unstated geo-political goal of establishing Portuguese-speaking Brazilian citizens near the borders of the country (Foresta, 1991).

A major component of the colonization programs was road construction and improvement. By the late 1970s the road infrastructure was so poor that only 60 percent of the small farmer plots were accessible during the dry season and only 10 percent during the rainy season (Skillings and Tcheyan, 1979). The lack of adequate transportation created major obstacles for marketing crops and obtaining services (e.g., health, education) (Millikan, 1988). To meet the need for improved transportation, the main highway through Rondônia, BR-364, was paved amid much controversy regarding its potential ecological impact (Goodland and Irwin, 1974). The completion of the road in 1984 greatly facilitated immigration into Rondônia.

The clearing of forests in Rondônia is correlated with road development (Frohn *et al.*, 1990). When the colonists move into the state, they cut the forest adjacent to the roads


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with the intent of establishing agriculture. Only a few of the most valuable tree species are harvested; most are cut and burned. The farmers are rarely able to support their families and most frequently move away from their original lot after a few years. The result has been major deforestation with little economic gain for the colonist.

The present model is being applied in the Ouro Preto colonization area, which is located along the BR-364 highway in central Rondônia. Ouro Preto was created in 1970 and was conceived as an ideal colonization project. It contained 4,011 $km^2$ of approximately 100-ha lots on some of the territory's most fertile soils. As word spread concerning the good agricultural conditions, more and more colonists moved to the region. Although initial plans were to have only 500 families in Ouro Preto, by 1974 an estimated 4,000 migrant families had obtained lots (Mueller, 1980), and by 1987 5,098 families were settled (Becker, 1987; Millikan, 1988). Soon other colonization projects were established to meet the ever increasing demand for land. Local soil conditions, hydrology, and fertility were not considered in designing the lot layout. The lots were rigidly laid out along roads in a grid 4 km apart. Although much of the land in the original colonization area was fertile, this was not universal, yet it was assumed the colonists could be equally productive on all soil types.

## Integrated Socioeconomic and Ecologic Model

To understand the effects of alternative land management, a simulation model called Dynamic Ecological - Land Tenure Analysis, or DELTA, has been developed that integrates a socioeconomic model of colonization and an ecological model of forest clearing and carbon change. The modeling system estimates patterns and rates of deforestation under different immigration policies, land tenure practices, and road development scenarios (Figure 1) (Southworth *et al.* (1991) describe the current model in some detail). The code is written in FORTRAN and runs on a personal computer. A user-friendly interface written in the C compiler language facilitates changing initial conditions or parameter values and provides graphical output.

DELTA can be classified as a stochastic, dynamic micro-simulation model. While the ecological effects of land-use change are evaluated at the region-wide scale, the dynamics of lot use and tenant farmer movement are simulated within DELTA at the micro-spatial lot and tenant specific level. By tracking the history of individual lots and tenants, the resulting aggregate patterns of land-use change are more likely to reflect the human settlement process; offering the possibility in the future for prescriptive application of the modeling system outputs to management. By introducing stochastic elements into many of the lot selection and land-use decisions, DELTA allows realistic simulation of ecological as well as socioeconomic impacts by averaging over multiple computer runs, for a single set of parameter inputs.

DELTA consists of three linked sub-models that simulate settlement diffusion, land-use change, and carbon release respectively. The settlement diffusion sub-model allocates and tracks tenant farming families among lots. Selection of a particular lot is based upon lot size, three indices of agricultural suitability based upon soil quality and physical aspect, distance to the nearest market along paved and feeder roads, and length of an occupant's current tenure. The simulation allows tenants to move between lots, multi-tenant lots to occur, and lots to be coalesced into large pastures.

Land-use changes are currently inputs to the model. Given suitable data, they can also be computed based on realized net revenues represented as crop prices minus crop transportation and production costs. For the Rondônia case study, the mix of land uses on a particular lot is taken to be some combination of annually cropped land, perennially

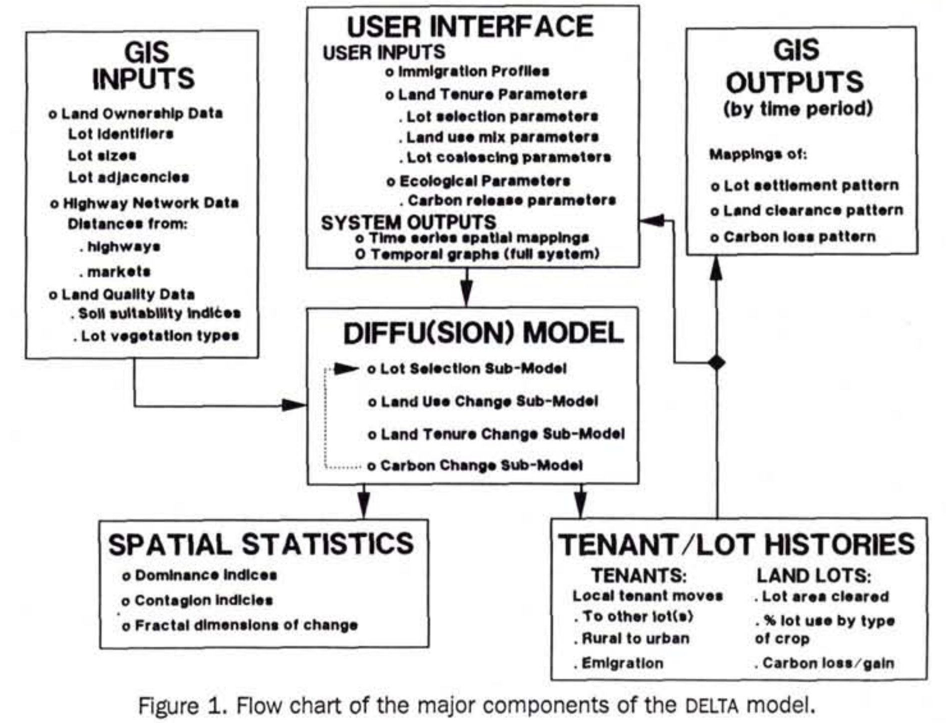


Figure 1. Flow chart of the major components of the DELTA model.

TABLE 1. ECOLOGICAL EFFECTS OF LAND-USE PATTERNS.

| Characteristics of Clearing | Effect |
|---|---|
| Intensity of use | Loss of soil fertility |
| Total area deforested | Carbon release, land degradation |
| Size of clearing | Soil erosion, forest reovery times, loss of mycorhizal associations |
| Size of forest patches | Decline in species diversity |
| Extent of forest edge | Wildfire damage |
| Spatial arrangement of clearings | Restrictions on animal movements, spread of disturbances |

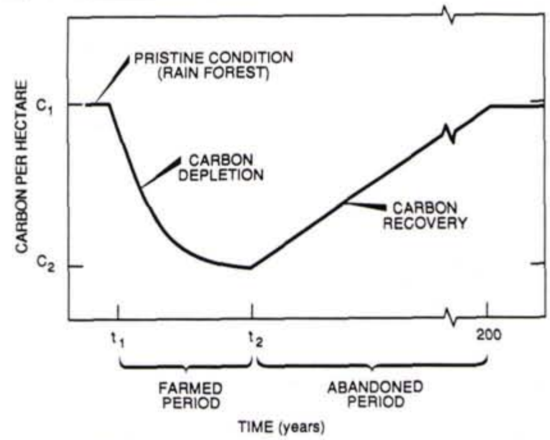


Figure 2. Piece-wise continuous carbon release curve.

cropped land, animal grazing, fallow, and undeveloped forest. For example, one scenario of the model may stipulate that, in the first year of tenure, a family may grow only annual, subsistence crops. In subsequent years they may plant perennial crops. Adjacent lots can be coalesced into one large pasture, depending on the amount of land already cleared for pasture in each lot.

The initial measure of ecological impact developed within DELTA is an estimate of the amount of land cleared and carbon released from each lot over time. It is intended that the model also be used to estimate other effects of clearing (Table 1). The estimate of carbon released from terrestrial sources to the atmosphere is based on a piece-wise continuous curve of the carbon per hectare (ha) in soil and vegetation under pristine conditions, farming or pasture use, and abandonment (Figure 2) (based on the approach of Houghton *et al.* (1983)). For the Rondônia example, the pristine forest is estimated to have 170 Mg/ha of carbon (Brown and Lugo, 1990). This value is multiplied by the number of hectares in the lot to obtain initial carbon values for the lot. With farming or pasture use, the initial level of carbon undergoes a negative exponential decline. A carbon loss rate per hectare of $e^{-0.19}$ is obtained by assuming that long-term farms or pasture would be in place 15 years at which time 10 Mg/ha of carbon remain on the lot (following the relationship for productivity given in Serrão and Toledo (1990) and using the values presented in John (1973), Lang and Knight (1979), and Swift *et al.* (1979)). Once a lot is abandoned by a tenant, if it is not immediately re-occupied, its carbon content is then assumed to increase linearly as vegetation regenerates itself slowly. This recovery rate will vary with the type and inten-

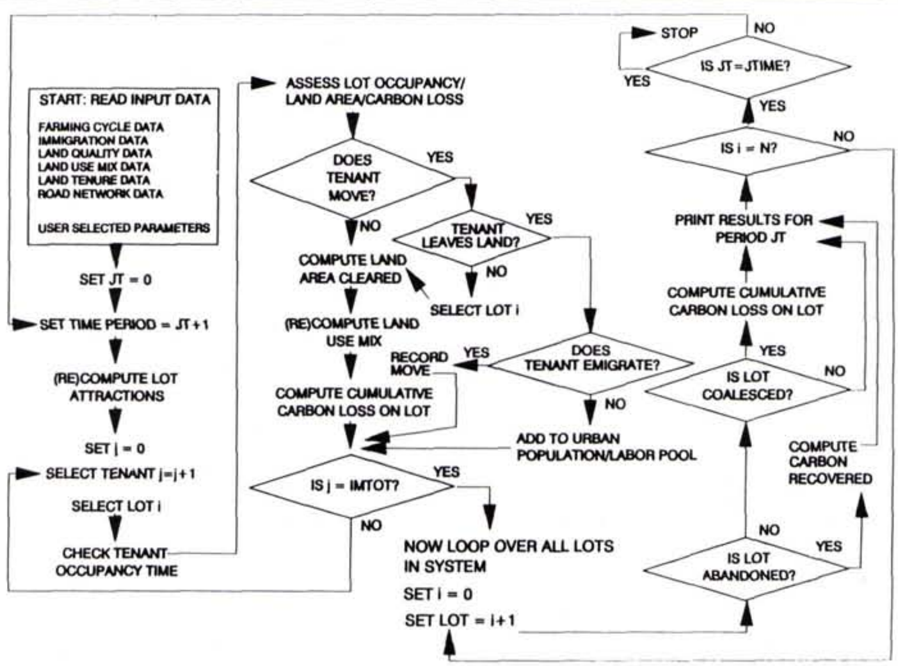


Figure 3. Details of data and models used in the study of land-use change. In the diagram, "JTIME" is the total number of years the model is allowed to run, "JT" tracks the current year, "j" is the potential colonist entering the area, "IMTOT" is the total number of colonists entering in the given year, "i" is the lot under consideration, and "N" is the total number of lots.

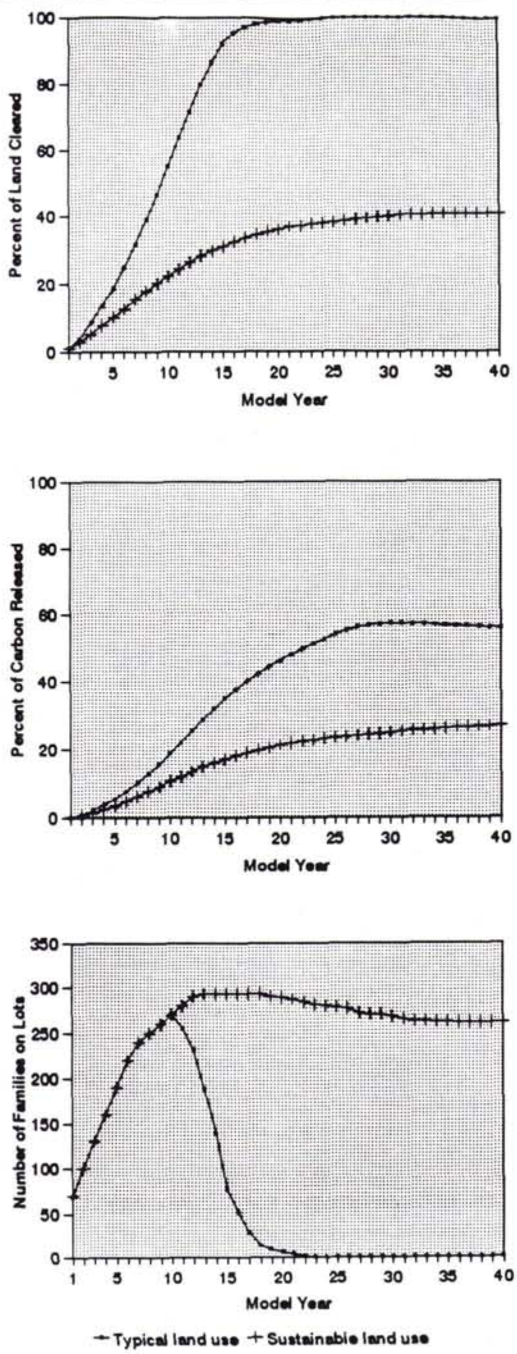


Figure 4. Projected land clearance, carbon release, and families remaining on lots based on activities of typical colonists and a sustainable agriculture scenario.

sity of land clearing practice. If a lot is reoccupied, the carbon content will proceed along an exponential decline beginning at the level of carbon that is in place when the farmer settles on the lot.

It is the linking of mapped data and models that permits a spatially explicit approach to land-use modeling and makes the model apply to central Rondônia. The model itself is designed to be generally applicable to situations where lots are laid out along transportation routes. Using ARC/INFO on a Microvax 3500 computer, we constructed a spatially explicit database consisting of vegetation, transportation networks for different time periods, pasture suitability, and agricultural suitability of Rondônia, and lot boundaries of Ouro Preto (Figure 3). These data set the initial conditions for each of the lots tracked in the FORTRAN model. The vegetation and suitability data were digitized from the RADAMBRASIL 1:1,000,000-scale maps obtained from a radar image study of the Amazon (RadamBrazil, 1978a; 1978b). The transportation networks were digitized from road maps produced by the Department of Roads in Rondônia (DER, 1988) and provide statewide coverage for 1979, 1982, and 1988. The lot boundaries in the study sites were digitized from blueprint maps by the National Council for Colonization and Agrarian Reform in Brazil.

#### Field Interviews with Farmers

Farmers on 91 lots in the Ouro Preto region were interviewed in August and November 1991 to provide information on the backgrounds of the colonists, current and past farming techniques, expenses, transportation used for produce, productivity, and the role of agricultural extension services (Pedlowski and Dale, 1992). Analyses of these data can suggest major features responsible for the land-use changes in Rondônia.

## Analyses

#### Model Scenarios

The model is applied to a set of 294 lots within the colonization area of the Ouro Preto Integrated Colonization Project. The model contrasts (1) the typical scheme of colonists burning the tropical forest, planting annual and perennial crops, followed by pasturing, and finally abandoning their lots with (2) sustainable cultivation practices in which farmers plant a diversity of crops and allow some of their farm land to grow into perennial tree crops from which products can be harvested (e.g., rubber, cocoa). The two scenarios considered are meant to represent activities of the typical farmers in Rondônia and farmers who use innovative techniques and grow perennial tree crops but have no income from milk or cattle (the "sustainable" case).

The typical land-management case simulates land-use activities that occur in central Rondônia as reported from a variety of studies (Leite and Furley, 1985; Millikan, 1988; Coy, 1987). During their first seven years on a lot, farmers generally clear forest until about half of the lot is cleared. Typical farmers plant annual and perennial crops during the first years and pasture in subsequent years, and they abandon parts of the lots to fallow vegetation beginning about year four.

The sustainable scenario simulates an innovative farm management system based on observations of a few farmers in the area (Dale *et al.*, 1993b). Those farmers used innovative farm management practices such as growing predominately perennial crops and intercropping trees such as rubber and cocoa. The farmers did not have pasture or cattle but averaged more than twice the income in 1990 from perennial crops as the other farmers in the region. The innovative farmers were simulated to have a high probability of staying on the lot (a 90 percent probability of not moving during any one of the first ten years) although soil degradation can act to override that probability. For the first four years that a farmer is on the lot, five hectares are cleared every year. For the first two years all of the land is planted into annual crops or pasture, but in years three and four half of the cleared land is

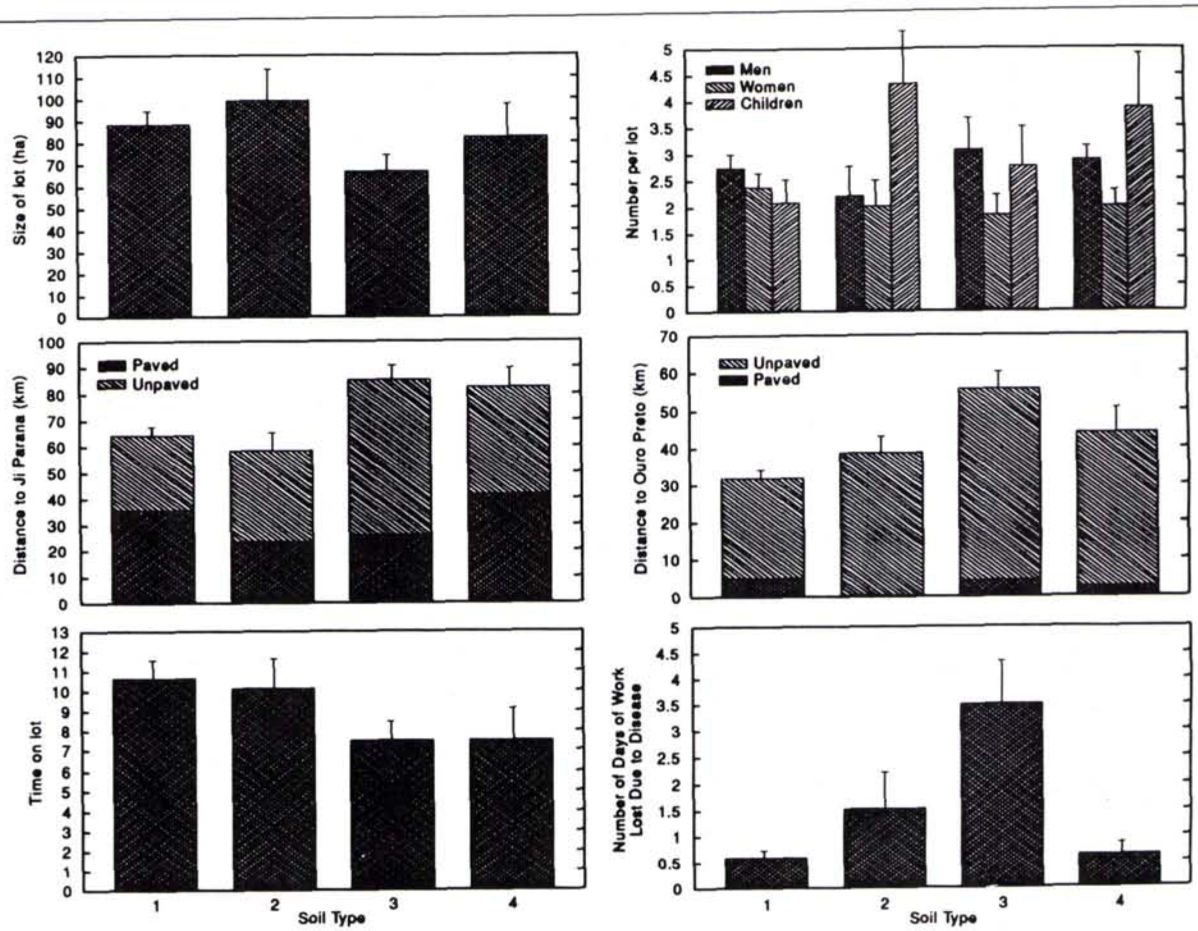


Figure 5. Histograms of lot size, family size, distance to the major markets of Ouro Preto and Ji Parana, time on lot, and work days lost to illness by the four soil types (1 = good soils, 2 = moderate, 3 = restricted, and 4 = unsuitable). Bars indicate standard errors.

planted in perennial tree crops, and by year five all of the cleared land on the lot is in perennials.

Both simulation scenarios are initiated with identical conditions. Farmers can settle on any one of the 294 lots that have an average lot size of 101 ha ranging from 53 ha to 120 ha. Lots are characterized by the spatially explicit pattern of natural vegetation and soils in central Rondônia. Distances to the major market along primary and secondary roads are calculated by using the 1988 primary and secondary road network within a geographic information system (Dearstone *et al.*, 1993).

Colonist families are introduced into the area in a regular pattern: 70 families the first year, 30 families per year in years 2 to 6, 20 families in year 7, and ten families per year for every year thereafter. In the simulation, colonists choose an appropriate lot based upon lot history, vegetation and soil conditions, distance to market, and lot size, and they farm it until conditions cause them to move elsewhere. After leaving a lot, half of the farmers stay in the 294 lot region, and the others move away.

### Analysis of Field Interviews

The interview data were grouped by the major soil types to discern if there was any pattern in farming practices based upon soil differences. This division arises because of Rondônia being selected for the colonization programs based on its exceptionally good soils for the Amazon basin. In reality, the soils range from good to unsuitable for agriculture (DNPM/RADAMBRASIL, 1978). Good soils present no to light growth limitations for a large number of annual and perennial crops that are climatically adapted to the region. Good yields are expected for a period of 20 years, when the yields gradually start to decrease. Moderate soils present light to moderate growth limitations for a large number of crops. Good yields are expected for 10 years, but yields are expected to decline thereafter. Restricted soils present moderate to severe growth limitations for climatically adapted crops. Medium yields can be expected for the first few years, but they will decline within a period of 10 years. Unsuitable soils present strong limitations for farming a large number of crops, and yields are expected to be low.

## Results

### Model Projections

The typical and sustainable model scenarios project different amounts of forest clearing (Figure 4). Almost all of the forest is cleared by year 18 in the typical land-use scenario. This large scale clearing reflects not only the clearing done by individual farmers, but also the sequential ownership of most

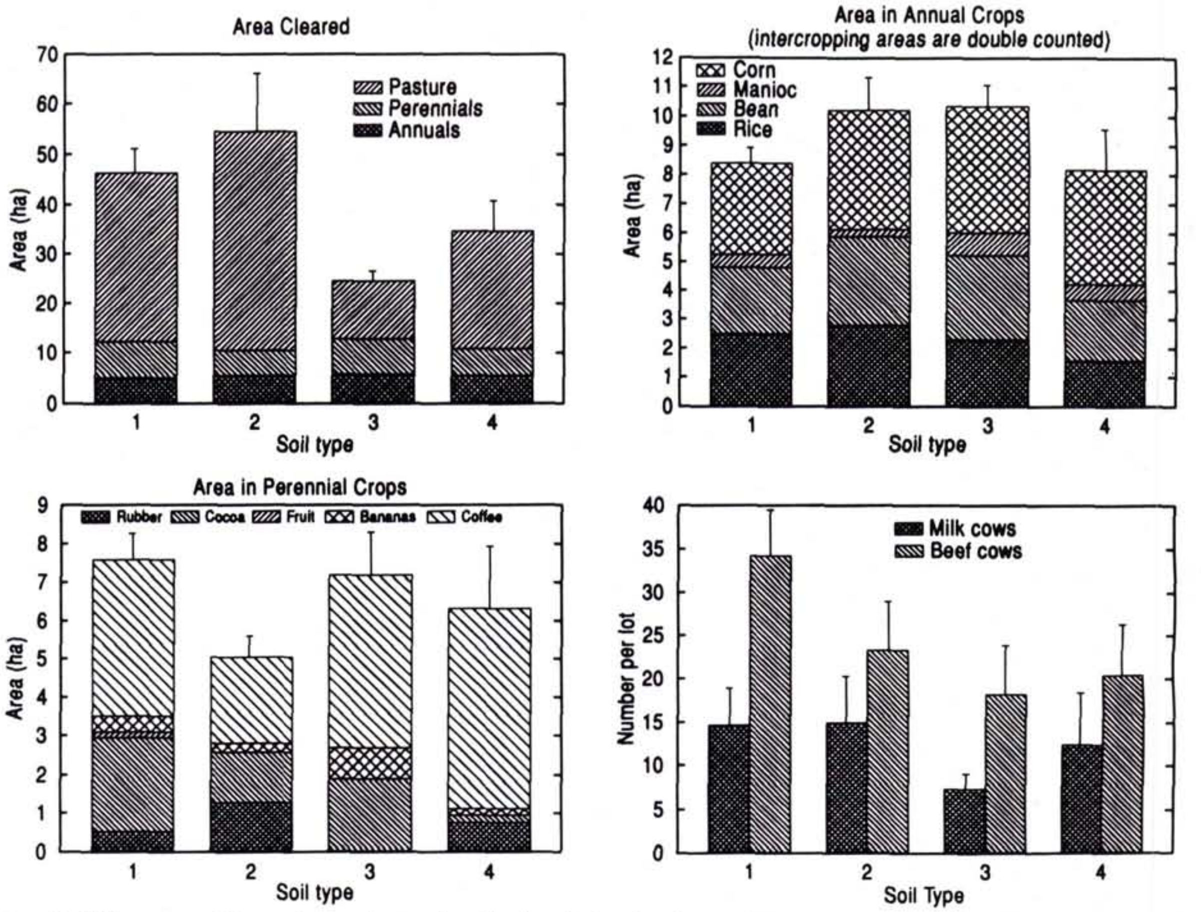


Figure 6. Histograms of type of cropping and cattle density for the four soil types (1 = good soils, 2 = moderate, 3 = restricted, and 4 = unsuitable). Bars indicate the standard error for the area in pasture, for the total area in all annual crops, for the area in coffee, and for the number of cows.

lots. Because the sustainable scenario projects little turnover in lot ownership, forest clearance approaches 40 percent and appears to stabilize by year 25.

The amount of carbon released from the cleared lots is a function of the different land-use scenarios (Figure 4). The typical land use is projected to cause a gradual increase in carbon release that peaks at about 55 percent of the original carbon by model year 27. Carbon release never approaches 100 percent because even when the forest is cleared, carbon is retained in the soil, crops, and weedy vegetation on the land. The slight decline in percent carbon release after model year 30 occurs because much of the land is abandoned and carbon accumulates in the regrowing vegetation. The sustainable scenario projects a slow but steady increase in the amount of carbon released that has attained 25 percent of the original carbon by model year 40.

The number of families on the lots over time shows that the sustainable scenario is able to support farmers for the full 40-year projection (Figure 4). The typical land-use scenario simulates an increase in the number of families on the lots up to the time at which more than 65 percent of the land has been cleared and soil quality is greatly reduced by the overuse of the land. At model year 10 for the typical case, the number of families on the lots begins to decline. No families can be supported after year 22.

**Results from Interviews**

The interviews with farmers in the Ouro Preto region show that a number of factors pertinent to farming success differ by the four major soil types. There are differences in regard to lot size, distance to markets, and time on lot (Figure 5). No differences occur for the number of men or women on a lot, but there are fewer children on the good and restricted soils. This could be important because older children can help with both field and household chores. The extra help is particularly important during times of illness. The loss of work due to disease differs by soil type with farms on the restricted soils having a particularly high number of work days lost.

Cropping also differs by soil type (Figure 6). The unsuitable and restricted soils have less area in pasture which may reflect the shorter time the farmers have been on these lots. Of the area in annual crops, there are no significant differences between the soil types. However, the area in perennial crops differs by soil type in the area planted to the major crops: coffee, rubber, cocoa, fruit, and bananas. Coffee is the major perennial crop both in terms of area planted and income received (Pedlowski and Dale, 1992), but significantly less coffee is planted on moderate soils.

The number of cattle also differs by soil type (Figure 6). The good soils have the largest number of beef cows, and the

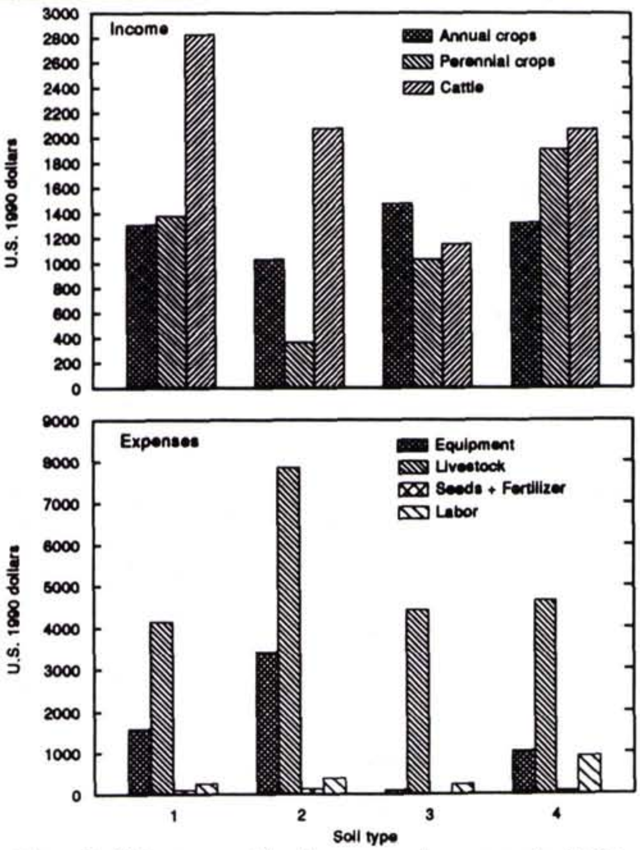


Figure 7. Histograms of the income and expenses in 1990 for the four major soil types (1 = good soils, 2 = moderate, 3 = restricted, and 4 = unsuitable). Farm equipment includes hand tools, mechanical machinery, and small carts used to transport supplies, produce and equipment on the farm.

moderate soils have the least milk cows. This difference is ironic because Ouro Preto was selected for colonization based upon the hypothesis that the good soils would be appropriate for supporting family farms that specialized in perennial crops (Stone, 1992).

However, most of the farm income comes from cattle (Figure 7). The relative annual income from cattle is particularly high for the good and moderate soils. The major expenses on all soils are associated with the purchase and care of livestock. Of course, both income and expenses will vary from year to year depending on market conditions.

## Discussion

The simulated land-use conditions for typical farmers reflect the observed land-use changes in central Rondônia (as based on recent field interviews (Dale and Pedlowski, 1992) and images from satellites). There is a high turnover of colonist families (Pedlowski and Dale, 1992; Millikan, 1988). Satellite imagery illustrates that the area is being cleared at a very rapid rate (Stone *et al.*, 1989).

Remotely sensed data are useful to test the changes in land use predicted by spatially explicit models. Satellite imagery can provide measures of the amount and pattern of deforestation for large areas during recent decades (Dale *et al.*, 1990). Although there have been a number of studies of the use of remote sensing to estimate deforestation in Rondônia (see references in Setzer and Pereira (1991)), the majority of these are concerned with estimating the total area of forest cleared and do not address the patterns of land use at the lot level. For example, recent estimates for deforestation for the entire state of Rondônia range from 37,200 $km^2$ (Stone *et al.*, 1989) to 45,400 $km^2$ (Setzer and Pereira, 1991), but there have been no studies which have examined the patterns of broad-scale land-use change generated by human activities at the lot level. Initial comparisons suggest that the pattern of land clearing projected by the model for typical colonists is similar to that in the Ouro Preto region after 20 years (Dearstone *et al.*, 1993). We plan to validate DELTA by comparing land areas that have similar fractal or contagion values obtained from the model projections and from the remotely sensed data.

The model results show that extremes of resource management affect carbon storage and release in Rondônia (Figure 4). Simulations of farmers interplanting perennial crops with annual subsistence crops and allowing the land to recover during a fallow period suggest that there are a variety of benefits to sustainable agricultural systems in Rondônia. A smaller area of forest is cleared, less carbon is released to the atmosphere, and the families can remain for a longer time on a farm. In contrast, simulations of the typical short-term and intense planting cause an order of magnitude more carbon release than with sustainable agriculture. The simulations suggest that the rapid clearing will lead to almost complete deforestation within four decades of initial colonization.

The model demonstrates that land management practices by farmers do have a significant impact on the storage and release of carbon and the model provides a tool to evaluate impacts of various land management options. The simulations can be used to identify scenarios that might optimize economic and agricultural sustainability or reduce emigration.

The basic premise underlying the model is that deforestation is a socioeconomic process. The approach to studying regional impacts thus includes social data collected on site, spatially explicit data on soils and vegetation, models that link socioeconomic and ecologic processes, and spatial analysis tools. The approach captures much of the complexity that relates road building or changes in crop selection to clearing of new land. The model provides the potential to predict future trends in deforestation as a function of socioeconomic and political parameters. The approach could also be used to evaluate management strategies that might minimize the impact of changes on the tropical forests.

The question that needs to be asked based upon the interview data is, "Are the major features affecting farming success in central Rondônia included in the DELTA model?" The next question would be, "Is the relationship between factors affecting farming success appropriately modeled?" The answers to these questions should reflect our goal of not just modeling causes and effects of land-use change in Rondônia, but of developing a general model that is applicable to regions where colonization programs cause deforestation.

DELTA is designed to model the highest level of abstraction necessary to capture the details of the system. For example, farming systems are divided into annual, perennial, and pasture, but the crops composing each category are not tracked. The field interviews support the use of these general categories, for they do encompass the greatest differences between soils types (Figure 6). The data also confirm that farm inputs (e.g., fertilizer, seeds, equipment) are minimal in this area and have little effect on farm success.

The field interviews highlight the importance of disease to farming activities. DELTA includes a variety of factors affecting a farmer's initial choice of lot and decisions to remain on lot (lot size, distance to market, and farm history), but the effects of illness on farm decisions have not been modeled. The interview results make it clear that disease effects on work days should be a part of the model. The model structure allows for comparison of tradeoffs between time spent farming versus time spent mitigating disease (e.g., by digging ditches that would drain habitats suitable for mosquitos that transmit malaria). Using the model to assess potential impact of illness and mitigation efforts would be useful.

The goal of this exercise has been to use the DELTA model to bracket responses to reasonable extremes of land-use management and to start on the process of identifying causes of the differences in those responses. The field interview data have allowed us to identify components of the model that are adequate and deficient. Together, the model and data suggest that land-use changes in central Rondônia are a function of lot size, land-use history, initial soil and vegetation conditions, land-use choices (planting annual, perennial, or pasture), and effects of illness on work. To fully utilize the field data requires an analysis using simultaneous regression equations because multiple factors operate concurrently to influence farming success (e.g., soil type, lot history, family structure, distance to market, and land-use practices all determine net income and time a farmer remains on lot) (Marschak and Andrews, 1944; Hoch, 1958). A rigorous statistical analysis of the interview data is in progress.

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