CONF-9108232--1

DE93 005776

Simulating Spatial Patterns of Land-Use Change in Rondônia, Brazil

Virginia H. Dale[1], Frank Southworth[2], Robert V. O'Neill[1] and Aaron Rosen[1]

Oak Ridge National Laboratory[3]
P.O. Box 2008, Oak Ridge, Tennessee 37831-6038

Proceedings to be published by the American Mathematical Society
volume on "Some Mathematical Questions in Biology"
Robert Gardner, editor

November 9, 1992

---

[1]Environmental Sciences Division

[2]Energy Division

[3]Managed by Martin Marietta Energy Systems, Inc., under contract DE-AC05-84OR21400 with the U.S. Department of Energy.

Abstract. Large scale deforestation in the Brazilian state of Rondônia has resulted from massive colonization and has caused increases in atmospheric CO_2, soil degradation, loss of extractive resources, and disruption of indigenous populations. A simulation model has been developed that integrates colonization, socioeconomic, and ecological submodels to estimate spatial patterns and rates of deforestation under different immigration policies, land tenure practices, and road development scenarios. It is used to model the socioeconomic causes and ecological impacts of rapid deforestation in Rondônia. The simulation can be used to identify scenarios that might optimize economic and agricultural sustainability or reduce emigration. Spatial analysis of the simulation projections shows that very different patterns of deforestation can result depending on whether soil suitability, distance to market or lot size is the prime factor affecting a colonist's choice of a lot. Projections of the amount and pattern of deforestation under specific scenarios of land-use choice and management can be used to explore the socioeconomic and ecological implications of land-use change.

1. Introduction

Land-use change is one of the major factors affecting global environmental conditions. Prevalent types of land-use change include replacing forests with agriculture, mining or ranches; forest degradation from collection of firewood; and forest logging. A global effect of wide-scale deforestation is an increase in atmospheric carbon dioxide concentration, which may affect climate (Lugo and Brown, 1986; Post et al., 1990, Dale et al. 1991). Regional effects include a decrease in biodiversity (Wilson, 1988) and disruption of hydrological regimes (Shukla et al., 1990). Local effects include soil erosion, siltation, and decreases in soil fertility (Hecht, 1981; Buschbacher et al., 1988), loss of extractive resources (NRC, 1985; Fearnside, 1989), and disruption of indigenous populations (Souza, 1980).

Modeling land-use change requires combining socioeconomic and ecological factors because socioeconomic forces frequently initiate land-use change and are affected by the subsequent ecological degradation. This paper describes a modeling system that integrates submodels of human colonization and ecological impacts to estimate patterns and rates of deforestation under different immigration and road development scenarios. Road building has become a major factor in the rapid deforestation of previously inaccessible areas. Roads facilitate colonization, allow access to large machines, and provide transportation routes for export of raw materials and produce. The simulation modelling system is being developed initially as a tool for analyzing conditions in the Brazilian state of Rondônia.

2. Case study: roads lead to deforestation in Rondônia, Brazil

Rondônia is located in the south central portion of the Amazon Basin and comprises an area of approximately 243,000 square kilometers. Nowhere has deforestation increased at a faster rate over the past two decades than in Rondônia (Malingreau and Tucker, 1988). Since the early 1970's the Brazilian government has implemented road construction and colonization plans in an effort to relieve the land tenure problems in its over-populated coastal cities, to utilize the resources of the vast undeveloped rainforest, and to establish Brazilian residents in the Amazon (Frohn et al., 1990). Colonization programs in Rondônia successfully attracted a large number of migrants because soil quality there, although not good, was much better than in other areas of the Amazon.

The majority of the migrants who enter Rondônia are assigned to an area of forest in official colonization programs, clear a tract of that forest, and plant agricultural crops. The acidic soils are temporarily improved by the organic compounds released from burning the forest cover, and crops grow well for a few years. Without careful soil management, acidity returns and the soils cannot sustain crops (Frohn, et al., 1990). The land may then be used as pasture for a few years before it is abandoned.

Land use follows a typical pattern although site quality influences farming methods and yields. During the first four years of farming, crops such as rice, corn, coffee, beans, or manioc are planted. Production of these crops becomes infeasible as soil acidity increases and as crops become more susceptible to pests and disease. Following the decline of agriculture, many farmers plant pasture grasses to raise a small number of cattle (see Tucker et al., 1984, 1986; Frohn et al., 1990). In other Brazilian colonization projects, cattle pastures eventually dominate the landscape (Fearnside 1983, 1984; Stone et al., 1991). Newcomers taking control of abandoned or unoccupied lots are often more likely to plant pasture instead of crops because pasture is much easier to farm. Also, newcomers appear to have more capital to invest in cattle than did the original settlers. Unfortunately, under current practices the land does not sustain cattle ranching or any other type of farming on fully cleared land beyond 6 to 8 years after initial cultivation because the soil conditions degrade rapidly. At that time, the farmer either cuts more forest and begins the land degradation process anew, or abandons the land and moves elsewhere.

The result of heavy migration into Rondônia and clearing forest for farming is rapid and large-scale deforestation. The 1987 estimates of total deforested area range from 16% to 19% of the state (Booth, 1989). In 1979, only 1434 km of permanent roads existed in Rondônia (IBGE, 1979a, 1979b). By 1988, 25,324 km of roads had been established (DER, 1988), an increase of over 1600%. Deforestation occurs not only on the road path itself, but also on adjacent areas as the road permits access to land for farming. If current rates of deforestation continue, all forested land in Rondônia would be cleared by the year 2000. Application of the model to Rondônia allows researchers and planners the opportunity to evaluate the potential effects of various road development and immigration scenarios on deforestation and its environmental and socioeconomic consequences.

3. Model development

The model simulates the spatial effects of colonization on land use change. The Dynamic Ecological - Land Tenure Analysis model (DELTA) permits ecological effects to be evaluated at the aggregate, region-wide level and the dynamics of land use pattern formation and change to be simulated at the micro-spatial, land lot and farmer specific level. By tracking not only the history of each farm lot (which average 100 ha), but also the history of colonists on the land, greater care can be taken to ensure that the resulting (aggregate) land use patterns appropriately reflect the human settlement process. The tracking of each lot should also allow DELTA to become a prescriptive tool with which settlement policy options may be evaluated.

The micro-spatial approach to simulation allows DELTA to be used to examine a wide variety of impacts of the land clearing process associated with a particular settlement pattern. Different patterns of land use may have similar effects on total land area cleared for cultivation, number of families settled, or the amount of food and other goods produced in the short term. However, the individual spatial and temporal aspects of each settlement pattern may have different long-term ecological consequences. DELTA quantifies such differences and simulates the likely consequences of continuing the spread of particular land colonization and land tenure practices over time and space. The model has been used to contrast the effects of sustainable agriculture compared to the agricultural practices of the typical colonists (Southworth et al. 1991).

3.1 Model overview, inputs and outputs

DELTA is an integrated settlement diffusion, land-use change, and ecological change model. The simulation model is written in Fortran, and runs on a personal computer. Run times for a 3000 lot system (300,000 ha) and for a planning horizon of 50 years require no more than a few minutes. The flow chart (Figure 1) shows the major steps in the program which are described in more detail below. The model tracks the land use and migrant status of each lot over a period of years. Farmers can move between lots dependent on lot conditions and distance to market (as described below). Agricultural lots can be coalesced into pasture. Lots can be fragmented by division and during sales with two or more colonist families occupying a lot that was originally designated for one family. Coalescing of adjacent lots or fragmentation can occur randomly if a set of conditions have been met. For coalescing, the conditions include that a combined percentage of the cleared land area exceed a user- specified value, for large cleared areas are frequently combined under a single owner (Millikan 1988). Colonists leaving a lot either purchase a new lot, emigrate from the area, or become part of the local labor pool of landless workers.

DELTA uses both spatially explicit and non-spatial data as inputs (Figure 2). Spatially explicit data used to initiate the simulation model include lot size and location with respect to neighboring lots, distance to market and to primary and feeder roads, soil conditions, and original vegetation types. Data on roads (alignments, lengths, type of pavement), agricultural and pasture suitability of the soils, and vegetation types are entered into the geographic information system (GIS) that interfaces with the model. Each lot is assigned a set of numerical values corresponding to road distances, soil suitability and original vegetation type. As the model is run, data on the land-use history is recorded for each lot every year.

The non-spatial parameters that feed into the model include information about the size of the area, lot occupancy decisions (such as the proportion of a lot's area to be cleared each year), conditions for coalescing lots into pastures, criteria for changes over time in a tenant's mix of land uses on a lot, and choice variables that deal with conditions under which colonists may move to a new lot (Table 1). A user interface to the model requests values for each parameter and assists the user by providing example inputs. Simulation results are based on the specific initial conditions, highway building patterns, and population immigration and emigration conditions set by the user. Numbers of immigrants entering the region per year is currently an exogenous input.

Model outputs include spatial statistics and maps (Figure 2), as well as net region-wide impacts. Specifically, these include a time series of deforestation maps, changes in land degradation tied to the temporal and spatial pattern of deforestation, and aggregate statistics recording the effects of a particular settlement pattern on the spatio-temporal pattern of forest clearing and, in turn, the results of this land development on carbon release. Comparison of the spatial implications of particular land use scenarios includes potential effects on the broad scale pattern of forests, cleared areas, and secondary vegetation.

The model can be used to examine a variety of policy options and their effects. In particular, impacts of changes in highway network configurations, market sizes and associated infrastructure dynamics can be simulated within the overall modeling framework. For example, DELTA can accept new lot accessibilities at each simulated time interval based upon upgrades to the local or regional road network, or as a result of expansions of local urban markets. Alternative highway system design policies might, in this manner, not only be tested for their ecological impacts on a region but also have their development conditioned or constrained by past impacts. Future extensions of the model could involve the simulation of effects of deforestation on soil run-off, loss of biomass, the regional water balance, or loss of biodiversity.

3.2 Modeling settlement diffusion

The model begins with an initial set of conditions representing the region's natural vegetation and soil patterns; population size; spatial array of farm lots, road and markets; and existing land-use practices. In each model year, we introduce to the region as an exogenous variable the number of immigrant families, termed "colonists", and distribute these families among a set of available land locations or "lots". The availability of a lot can depend upon a number of case study-specific factors such as a pre-defined government or private sector program offering land to would-be colonists in pre-specified sizes. Where no such planning exists, lots may be selected from a grid of points distributed evenly over the landscape. In most cases we expect a combination of initially planned and unplanned lots. To accommodate this we define lot boundaries from a blueprint or use the Arc/Info GIS (ESRI 1990) to allocate lots on a cartesian coordinate basis, while recognizing existing public or private lot boundaries.

For each available lot, i, in the system, we calculate a relative lot attractiveness index of the form:

$$A_i = a_1X_{i1}+a_2X_{i2}+\ldots+a_kX_{ik} \qquad (1)$$

where X_{ik} is the value of attribute k measured on lot i, for k = {1, 2, ..., K} attributes, and where $a_1,\ldots,a_K$ are attribute weights specified by the user or derived on the basis of empirical evidence. The values of a_i range from 1 to 10 and can be used to evaluate how the attributes affect model projections. Because little is known about the effect of each attribute on lot attractiveness, the weights are equal in the default case. However, analysis of data on socioeconomic conditions and choices in central Rondônia (Pedlowski and Dale 1992) will provide information for determining realistic weighting values. The lot attractiveness attributes, ($\underline{X}$), may themselves be composite variables requiring prior computation. In the Rondônia case study, they include lot size, three soil quality indices of agricultural suitability (for annual crops, perennials and pasture), distance to the nearest local market via primary (paved) and local (unpaved, feeder) road access, and current carbon in the soils and vegetation of the lot. The carbon content of a lot decreases when the original vegetation is burned and when crops production declines with soil degradation but may increase wtih growth of perennial crops or fallow vegetation. A particularly interesting attribute is length of current lot tenure, as this affects both the lot's productivity and its mix of land uses. Both length of current lot tenure and usable lot size are updated each time period within DELTA, making them endogenous to the system.

The probability of a tenant selecting a specific lot i from the set available is based on a multinomial logit destination selection model of the form:

$$P_i = \frac{\exp A_i}{\sum_j \exp A_j} \tag{2}$$

for j = {1, 2, ..., i, ..., J} available lots (see Southworth, 1981, for example). The logit model is the most common spatial interactive model used by geographers, regional scientists, and transportation planners (Wrigley 1985). It is both mathematically tractable and based on a logistic response curve that reflects diminishing response to stimuli at extremes of the distribution. The relative choice probabilities, P_i, (which sum to 1.0 when taken over all available lots) are then used with a random number selection process to allocated lots to colonists. In this manner, a less attractive lot has some chance of being taken early in the settlement process: a common occurrence, since potential colonists, no matter what the land use situation, rarely have complete information at their disposal with which to select a site for development.

A currently exogenous input to the model is the average probability of a colonist moving after a specific number of years on a lot. For example, there may be an almost linear increasing probability of colonists leaving a lot (based on discussion in Coy 187 and Millikan 1988). We do not model colonists turnover to be a function of productivity because abandonment of lots is usually not related to farming experience but is determined by financial indebtedness, injuries, disease, or random events (e.g. marital problems) (Fearnside 1986). The same process as just described is used to select the number of colonists that move annually (except during the first year), based upon a discrete set of probability values. In the Rondônia example reported below, those colonist farmers with longer time on a lot are more likely to be selected to move, reflecting observed events. Such movements could also be made to depend on current soil quality.

The probability of a tenant making a particular series of moves over time is thus simulated as a product of the conditional probability of each individual move:

$$P_{(i1,i2,\ldots,iM)} = P_{i1}\ P_{i2}\ \cdots\ P_{iM} \tag{3}$$

where $P_{(i1,i2,\ldots,iM)}$ is the probability of a specific sequence of M moves, beginning with a move to lot i1 and ending with lot iM. Combining equations (2) and (3) gives

$$P_{(i1,i1,\ldots,iM)} = \prod_{m=1,M} \frac{\exp A_{im}}{\sum_{j\epsilon J(m)} \exp A_{jm}} \tag{4}$$

where jϵJ(m) implies summation over all lots available for use at tenant move m. With some rearrangement, this implies that

$$P_{(i1,i2,\ldots,im)} = \exp \sum_{m} [A_{im} - \ln \sum_{j\epsilon J(m)} \exp A_{j}\ ]. \tag{5}$$

In other words, the probability of a tenant moving into the region and then occupying specific land lots i through iM during M successive moves is an exponential function of the additive total utility of the lots chosen less a function of all available lot utilities summed over all movement periods.

If a colonist is selected to move, then the choice of his destination lot is modeled using equation 2. When available land becomes scarce, or if evidence suggests that some proportion of colonists emigrate from the region, then a test is made to see if one or more colonists are (randomly) allocated to be emigrants during a particular year. Currently, this test is based upon the probability of a colonist leaving the area after a given period of time or on a measure of land pressure (as a function of the number of immigrants divided by the number of available lots).

As a example of lot movement patterns, Figure 3 diagrams a single colonist family's three-lot history generated by DELTA. In this example there are three "waves" (time periods in DELTA) of colonization, with the dynamics of land occupancy and development tied strongly to the existing pattern of roads. Such a close association between land clearing and road development is very evident in Rondônia, making it a relatively simple spatial process to replicate.

3.3 Modeling land-use change

Currently, DELTA accepts as input a set of expected land-use parameters (Table 2). These parameters determine the combination of land uses to be found on a lot. They are allowed to vary over time. For the Rondônia case study, the mix of land uses on a particular lot includes undeveloped forest as well as some combination of annual cropping, perennial cropping, animal grazing, and fallow. For example, in the first year of tenure, a family may grow only annual, subsistence crops. In subsequent years they may plant perennial crops. A colonist may also put some cleared and previously cultivated land into grazing. The expected level of a lot's annual development, over all land use types, can be randomized within DELTA.

The land-use mix for a given type of development can be either an exogenous input or, given suitable data, can be computed on the basis of realized net revenues represented as crop prices minus crop transportation and production (and, if appropriate, land leasing) costs (see Wilson and Birkin, 1987, for example). For a region such as Rondônia, however, profit oriented land-use selection is complicated by the typically rapid fall in crop yields due to the rapid loss of soil fertility associated with current farming practices.

3.4 Modeling carbon release

The initial measure of ecological impact developed within DELTA is an estimate of the carbon released from vegetation and soil in each lot over time. This estimate is based on a piece-wise continuous curve of the carbon per hectare under pristine conditions, farming or pasture use, and abandonment (Figure 4), which is derived using the approach of Houghton et al. (1983). For the Rondônia example, the pristine forest is estimated to have 170 Mg/ha (Brown and Lugo, 1992), which is multiplied by the number of hectares in the lot to obtain an initial carbon value for each lot. With farming or pasture use, the initial level of carbon undergoes a negative exponential decline. For this case study, a carbon loss rate per hectare of $e^{-0.19}$ was obtained by assuming that long-term farms or pasture would be in place 15 years at which time 10 Mg/ha of carbon remained on the lot. Once a lot is abandoned, if it is not immediately re-occupied, its carbon content is then assumed to improve gradually as vegetation regenerates itself slowly on the (typically overworked) open land. A constant, linear rate of carbon return is used to model this effect. The slope of 0.32 is used if it is assumed that it takes 500 years for the carbon content of the forest to fully recover (Uhl et al. 1988). Thus regeneration is a very gradual process requiring a significantly longer time to recovery than the rapid process of land clearance initiated by settlement expansion.

Carbon content can serve as a surrogate ecosystem parameter to represent the biomass, nutrient status or successional status of a lot. In this case, carbon depletion can be used as a planning variable to set an upper limit on lot clearance level. While colonists don't respond to carbon loss per se, carbon depletion is related to soil degradation which occurs as a result of runoff, siltation due to overgrazing, or the removal of arboreal barriers to erosion. By linking lot degradation to the carbon content of a lot, we can experiment with carbon as a planning tool. For example, maximum lot tenure time (i.e., a colonist's continuous period of occupancy on a specific lot) could be made to vary according to the lot carbon content. This approach could be used to explore the effects of a land conservation strategy geared to preventing excessive land clearance unbroken by any form of effective forest cover. In this case lot attractiveness could be expressed in terms of the current carbon content of the lot, or carbon loss. For example, if $X_{k=1}$ refers to the measure of carbon content on a lot, then we can normalize A_i in (1) to provide a generalized lot attractiveness, or utility measure based upon carbon content, i.e.,

$$A^c_i = \frac{(a_1 X_{i1} + a_2 X_{i2} + \ldots + a_k X_{ik})}{a_1} \qquad (6)$$

In this way, depending upon whether a colonist improves or degrades his lot during occupancy, the attractiveness of a lot, A_i, may change noticeably over time.

5. Simulation conditions

A series of hypothetical simulations were run to explore the capabilities of the modelling system as a means to better understand the relationships between socioeconomic and ecologic aspects of land-use change. These simulations are based on an actual 294 lot system within the Ouro Preto region of Rondônia, using a series of land quality indices, an existing (1988) primary and feeder road pattern, and actual distances from each government designed lot to the single major market. One hundred and fifty colonists are allowed to enter the area over a 50 year period (70 colonists in year one and ten per annum over the next eight years).

The land-use clearing pattern simulated is representative of the typical Rondônian colonist's farming experience, based upon the evidence reported in the literature for some of the area (Frohn et al, 1990; Millikan, 1988; Fearnside, 1983, 1984, 1986; Leite and Furley, 1985) (Table 2). Settlers plant most of the land to annual crops during the first four years on a lot. Perennial crops are first planted in the second year, and about one third of the cleared land is in perennial crops thereafter. Land is first put into pasture in year four. As the soil qualities declines the proportion of land in fallow increases. Settlers are assumed to clear 5 ha the first year, 10 ha the second year, 15 ha the third year, and a declining area thereafter. Subsequent colonists can clear the remaining forest on a lot and start the land use cycle anew.

Lot sizes in the study area range from 53 ha to 120 ha, averaging 101 ha over the full 294 lots. There is an increasing probability of the settler moving off the lot with time (Southworth et al., 1991). For example, there is a 20% chance that an colonist family will move during the third year of occupancy, increasing to an 80% chance during the eighth year. Over a 50 year period a lot may be occupied by one or more (up to three) colonist families. The average occupancy period, taken over all colonists is typically 5 to 6 years with approximately 40 ha cleared per occupancy. If colonists remain beyond six years on a lot, carbon depletion is simulated to continue on these already cleared hectares according to the exponential decline shown in Fig. 4.

As a way to demonstrate the modeling approach, three scenarios are projected with DELTA. These scenarios examine how land use choices by the farmer can affect the amount and pattern of deforestation and carbon release. The weighting of the parameters which most affect a colonist's decision whether to settle a particular lot were varied. For the three scenarios the factors most heavily weighted (by a factor of ten) were, respectively, lot size, distance to market and soil suitability indices. These factors were chosen because they reflect the colonists understanding of the value of the lot.

6. Results

Varying the factor most heavily weighted for lot choice does affect the amount of deforestation but has little effect on the amount of carbon released (Figure 5). Percentage deforestation for the three scenarios varies from 80% to 100% with the soil suitability scenario resulting in the least deforestation. All of these simulations result in about 35% of the original carbon in the forest being released to the atmosphere. The carbon remaining on the site is retained in either the soil or residual vegetation, or is accumulated in the secondary vegetation and soils.

The observed pattern of deforestation projected by the three scenarios differs after year 10 (Figures 6, 7, and 8). In model year zero, all of these projections had 100% forest, which is rapidly cleared by the colonists' activities. Under the soil suitability scenario, lots are gradually cleared over the 50 year projection, but by year 40 some lots still retain 100% forest cover. In contrast, the other scenarios project that some of the forest is cleared from all of the lots by year 20. For the distance to market scenario, some of the lots retain 40 to 60% cover by year 40. For the lot size scenario, all but one of the lots is cleared by year 30, and that lot is 60 to 80% deforested.

Spatial analysis of the model projections provides a comparison between different scenarios. The following indices are used for comparison: dominance, contagion, and fractal dimension (O'Neill et al. 1988, Krummel et al. 1988). The dominance index generally indicates the degree to which one land use type dominates the landscape. The contagion index measures the extent to which land uses are aggregated or clumped. A high fractal dimension indicates great complexity of the shapes of the land-use patches. Together these indices provide a measure of the differences and similarities between the particular scenarios being implemented.

In these scenarios the landscapes are all dominated by the forest at the beginning of the simulations and by the cleared areas at the end (Figure 9). It is interesting that heterogeneity is highest for years 5 to 15 and then decreases (i.e., dominance increases) as more and more land is cleared. Thus, the management question that is revealed by the values of the dominance index is how can heterogeneity, which favors high biodiversity, be maintained past year 20.

The ranking of dominance values of the three simulations after 25 years corresponds to the environmental impact of the three scenarios. The scenario with lot size weighted most heavily is totally dominated by the cleared areas by year 30. The scenario with distance to market weighted has a mix of forest and cleared area remaining by the end of the projection. The soil suitability scenario still retains a complex pattern with forest mixed in with the cleared areas by year 40.

The contagion value is initially low for all scenarios but increases as land clearing continues (Figure 10). The scenario with lot size weighted most heavily quickly approaches a contagion value of one as more of the area is cleared. Although low contagion values have been associated with human activities that dissect the landscape (O'Neill et al. 1988), the opposite is true here. In this case, the high contagion values after 20 years of land use indicate the large amount of clearing that has occurred. There is little change in contagion for the scenario in which soil characteristics are most heavily weighted because the probability of a forested lot being adjacent to another forest lot changes little.

In general the three scenarios show a decline in the fractal dimension from years 10 to 25 (Figure 11). This decline in fractal dimension relates to an increase in human disturbance (Krummel et al. 1987). The increase in fractal dimension after year 25 occurs for those scenarios which are dominated by one large cluster of cleared land. Thus, the scenario in which soil suitability is most weighted has little change after year 25 because a complex mix of forest and nonforest land is retained.

7. Discussion

These simulation results suggest that land-use activities can occur which have similar amounts of carbon released but which result in different patterns of forest and clearings. The ability to project the pattern that might arise from land-use activities is important because the forest pattern can influence movements of animals that pollinate, disperse seeds, or are herbivores on the forest vegetation (Gardner et al. 1989). Collins (1990) recognizes three modes of movement of tropical forest animals. Animals such as sloths require the trees be close enough together that they can move from trunk to trunk. Monkeys and other arboreal animals use vines and tree limbs to swing from tree to tree. Winged animals such as bats and birds can fly between widely dispersed trees. Other animals see forest clearings or roads as a barrier to movement. Some soil microbes are restricted by the higher temperatures and lower soil moisture from moving into clearings. Peccaries, which are dispersers of seed for some tropical trees, tend not to cross roads. Forest patterns can also affect fire susceptibility and the spread of fire (Uhl and Kaufman 1990). Thus the spatial pattern of forest and clearing can have numerous impacts on the ecosystem.

The DELTA simulation model allows users to examine potential effects of socioeconomic and ecological interactions on the amount, rate, and pattern of land-use change. It is important to be able to consider all of these factors simultaneously in land-use planning. Finally, however, a note of caution should always accompany multi-stage simulation modeling systems. With so many factors acting and interacting within the simulation model, a great deal of care is required to understand the context in which each simulation exercise is carried out. The above examples should be seen at this time as demonstrations of the modeling approach. However, the very act of setting up comparative simulations of the sort described here forces the analyst to consider carefully the often complex human and ecological implications of a particular land use policy. Indeed, as important as the predictions themselves may be, the process of education imparted by using such a model to assess alternative land tenure and road development policies may prove at least as useful in the long run. By making DELTA a highly modular, rule based system, in which such inputs as land tenure lengths, lot coalescing (or fragmentation) decisions, and land use mixing decisions are easily substituted, application to other areas of the world outside Rondônia should provide some very interesting comparison studies. While DELTA is still very much under development, the approach appears to be a promising and flexible one.

Acknowledgements

Foster Brown supplied some of the maps and other data. Barbara Jackson modified and ran the spatial analysis program. Richard Flamm and Robin Graham provided useful comments on an earlier draft of the manuscript. The research was sponsored by the ORNL Director's R&D Fund through the Global Environmental Studies Center, and by the Carbon Dioxide Research Program, Atmospheric and Climatic Change Division, Office of Health and Environmental Research, U.S. Department of Energy, under contract DE-AC05-84OR21400 with Martin Marietta Energy Systems, Inc.

References

Booth, W. 1989. Monitoring the fate of forests from space. Science 243: 1428-1429.

Brown, S., and Lugo, A.E. 1992. Biomass estimates for tropical moist forests of the Brazilian Amazon. Interciencia (in press).

Buschbacher, R., Uhl, C., and Serrao, E.A.S. 1988. Abandoned pastures in eastern Amazonia. II. Nutrient stocks in the soil and vegetation. J. Ecol. 76: 682-699.

Coy, M. 1987. Rondônia: Frente pioneira e programa polnoroeste. O processo de diferenciação sócio-econômica na periferia e os limites do planejamento público. Tübinger Geographische Studien 95:252-270.

Collins, M. (ed.) 1990. The Last Rain Forest: A World Conservation Atlas. New York: Oxford University Press.

Dale, V.H., Houghton, R.A., and Hall, C.A.S. 1991. Estimating the effects of land use change on global atmospheric CO_2 concentrations. Can J. For. Res. 21:87-90.

Departamento De Estradas De Rodagem, Rondônia (DER). 1988. Estado De Rondônia. Scale 1:1,000,000. Porto Velho, Brazil. M: ı.

Environmental Systems Research Institute (ESRI). 1990. ARC/INFO users Guide. ESRI, Redlands, Ca.

Fearnside, P.M. 1983. Land use trends in the Brazilian Amazon region as factors in accelerating deforestation. Environ. Cons. 19:141-148.

Fearnside, P.M. 1984. Land clearing behavior in small farmer settlement schemes in the Brazilian Amazon and its relation to human carrying capacity. pp. 255-271. IN A.C. Chadwick and S.L. Sutton (eds.), Tropical Rain Forest: The Leeds Symposium. Leeds Philosophical and Literary Society, Leeds, U.K.

Fearnside, P.M., 1986. Human carrying capacity of the Brazilian rainforest. Columbia University Press, New York, 293 pp.

Fearnside, P.M. 1989. A prescription for slowing deforestation in Amazonia. Environment 31:17-40.

Frohn, R.C., Dale, V.H., and Jimenez, B.D., 1990. Colonization, road development and deforestation in the Brazilian Amazon Basin of Rondônia. ORNL\TM-11470, Oak Ridge, Tennessee.

Gardner, R.H., O'Neill, R.V., Turner, M.G., and Dale, V.H. 1989. Quantifying scale-dependent effects of animal movement with simple percolation models. Landscape Ecology 3: 217-229.

Hecht, S.B., 1981. Deforestation in the Amazon Basin: Magnitude, dynamics, and soil resource effects. Studies in Third World Societies 13: 61-110.

Houghton, R.A., Hobbie, J.E., Melillo, J.M., Moore, B., Peterson, B.J., Shaver, G.R. and Woodwell, G.M., 1983. Changes in the carbon content of terrestrial biota and soils between 1860 and 1980: Net release of CO_2 to the atmosphere. Ecol. Monogr. 53: 235-262.

Instituto Brasileiro De Geographia E Estatistica (IBGE). 1979a. Porto Velho. Rio de Janeiro, Brazil.

Map, Scale 1:1,000,000.

Instituto Brasileiro de Geographia E Estatistica (IBGE). 1979b. Guapore. Rio de Janeiro, Brazil. Map, Scale 1:1,000,000.

Krummel, J.R., Gardner, R.H., Suhihara, G. and O'Neill, R.V. 1987. Landscape patterns in a disturbed environment. Oikos 48:321-324.

Leite, L.L. and Furley, P.A. 1985. Land development in the Brazilian Amazon with particular reference to Rondônia and the Ouro Preto colonization project. In Change in the Amazon Basin. J. Hemming, ed., Manchester: Manchester University Press.

Lugo, A.E., and Brown, S., 1986. Steady state ecosystems and the global carbon cycle. Vegetatio 68: 83-90.

Malingreau, J.P., and Tucker, C.J., 1988. Large-scale deforestation in the southeastern Amazon basin of Brazil. Ambio 17(1): 49-55.

Millikan, B.H. 1988. The Dialectics of Devastation: Tropical Deforestation, Land Degradation, and Society in Rondonia, Brazil. M.A. Thesis, University of California, Berkeley.

O'Neill, R.V., Krummel, J.R., Gardner, R.H., Sugihara, G., Jackson, B., DeAngelis, D.L., Milne, B.T., Turner, M.G., Zygmnuht, B., Christensen, S.W., Dale, V.H., and Graham, R.L., 1988. Indices of landscape pattern. Landscape Ecology 1:153-162.

National Research Council (NRC), 1985. Underexploited tropical plants with promising economic value. National Academy Press, Washington, D.C.

Pedlowski, M., and Dale, V.H. 1992. Land-use practices in Ouro Preto do Oeste, Rondônia, Brazil. ORNL/TM-12062. Oak Ridge, Tennessee.

Post, W.M., Peng, T.-H., Emanuel, W., King, A.W., Dale, V.H. and DeAngelis, D.L., 1990. The global carbon cycle. American Scientist 78(4): 310-326.

Shukla, J., Nobre, C., and Sellers, P., 1990. Amazon deforestation and climate change. Science 247:

1322-1325.

Souza, Martins J., 1980. Fighting for land: Indians and posseiros in legal Amazonia. IN Land, people and planning in contemporary Amazonia, ed. F. Barbira-Scazzocchio, 80-94. Centre for Latin American Studies, Occasional Publication No. 3. Cambridge University Press, Cambridge, England.

Southworth, F., 1981. Calibration of multinomial logit models of mode and destination choice. Transportation Research 15A: 315-325.

Southworth, F., Dale, V.H., O'Neill, R.V. 1991. Contrasting patterns of land use in Rondônia, Brazil: Simulating the effects on carbon release. International Social Science Journal 130:681-698.

Stone, T.A., Brown, F., and Woodwell, G.M. 1991. Estimation, by remote sensing, of deforestation in Central Rondônia, Brazil. Forest Ecology and Management 38:291-304.

Tucker, C.J., Holben, B.N., and Goff, T.E. 1984. Intensive forest clearing in Rondônia, Brazil, as detected by satellite remote sensing. Remote Sens. Environ. 15:255-261.

Tucker, C.J., J.R.G. Townsend, Goff, T.E., and Holben, B.N. 1986. Continental and global scale remote sensing of land cover. pp. 221-241 IN Trabalka, J.R. and D.E. Reichle (eds), The Changing Carbon Cycle A Global Analysis. Springer-Verlag.

Uhl, C., and Kaufman, J.B. 1990. Deforestation, fire susceptibility, and potential tree responses to fire in the eastern Amazon. Ecology 71(2):437-449.

Uhl, C., Buschbacher, R., Serrao, E.A.S. 1988. Abandoned pastures in eastern Amazonia. I. Patterns of plant succession. J. Ecology 76:663-681.

Wilson, A.G., and Birkin, M., 1987. Dynamic models of agricultural location in a spatial interaction framework. Geographical Analysis 19.1: 31-56.

Wilson, E.O. (ed.), 1988. Biodiversity. National Academy Press. Washington, D.C.

Wrigley, N. 1985. Categorical Data Analysis for Geographers and Environmental Scientists.

Longman: London. 392 p.

Table 1. Parameters in DELTA.

Category	Parameter
System size	Number of land lots Number of time periods (years) Number of new settlers in each time period
Lot selection and occupancy period	Maximum number of consecutive occupancies Minimum time between consecutive occupancies Number of lot attraction variables Lot occupancy option Weights on lot attraction variables Probability of colonist leaving after each time period Logit choice model sensitivity (distance decay rate)
Coalescing	Minimum joint level of clearing Probability that lots will coalesce Profit per unit of coalesced land Minimum proportion of a lot that must be developed Maximum number of neighboring lots
Land use mix	Rate of change to a given land use type Percent of a lot's land used in a given land use type for a given tenure
Land development	Land quality effect Tenure time effect Transportation cost Minimum area that must be developed Ratio of land productivity to land quality Unit transportation cost by land use
Carbon loss	Initial carbon on forested lot (Mg/ha) Rate of carbon return Minimum carbon (proportion of initial carbon) Rate of decrease in carbon

Table 2. Input information for the land-use change component of the model.

Model year	Probability of tenants leaving lot	Average amount of land cleared (ha/yr)	Percent land use (of the cleared area)			
			Annual	Perennial	Fallow	Pasture
1	0	5	100	0	0	0
2	0.1	10	80	20	0	0
3	0.2	15	70	30	0	0
4	0.3	10	40	30	10	20
5	0.4	5	30	30	20	20
6	0.4	5	20	30	20	30
7	0.6	0	10	40	20	30
8	0.8	0	20	30	20	30
9	0.9	0	20	30	20	30
10	1.0	0	10	20	30	40

Figure Captions:

Figure 1. Flow chart showing major modeling steps in DELTA, emphasizing the land use change perspective.

Figure 2. DELTA as the centerpiece of a spatial analysis system.

Figure 3. Hypothetical four-lot farmer history.

Figure 4. Carbon release and recovery profile.

Figure 5. Percent land cleared and carbon released for the three scenarios.

Figure 6. Map of percent deforestation for the scenario with soil suitability weighted most heavily.

Figure 7. Map of percent deforestation for the scenario with distance to market weighted most heavily.

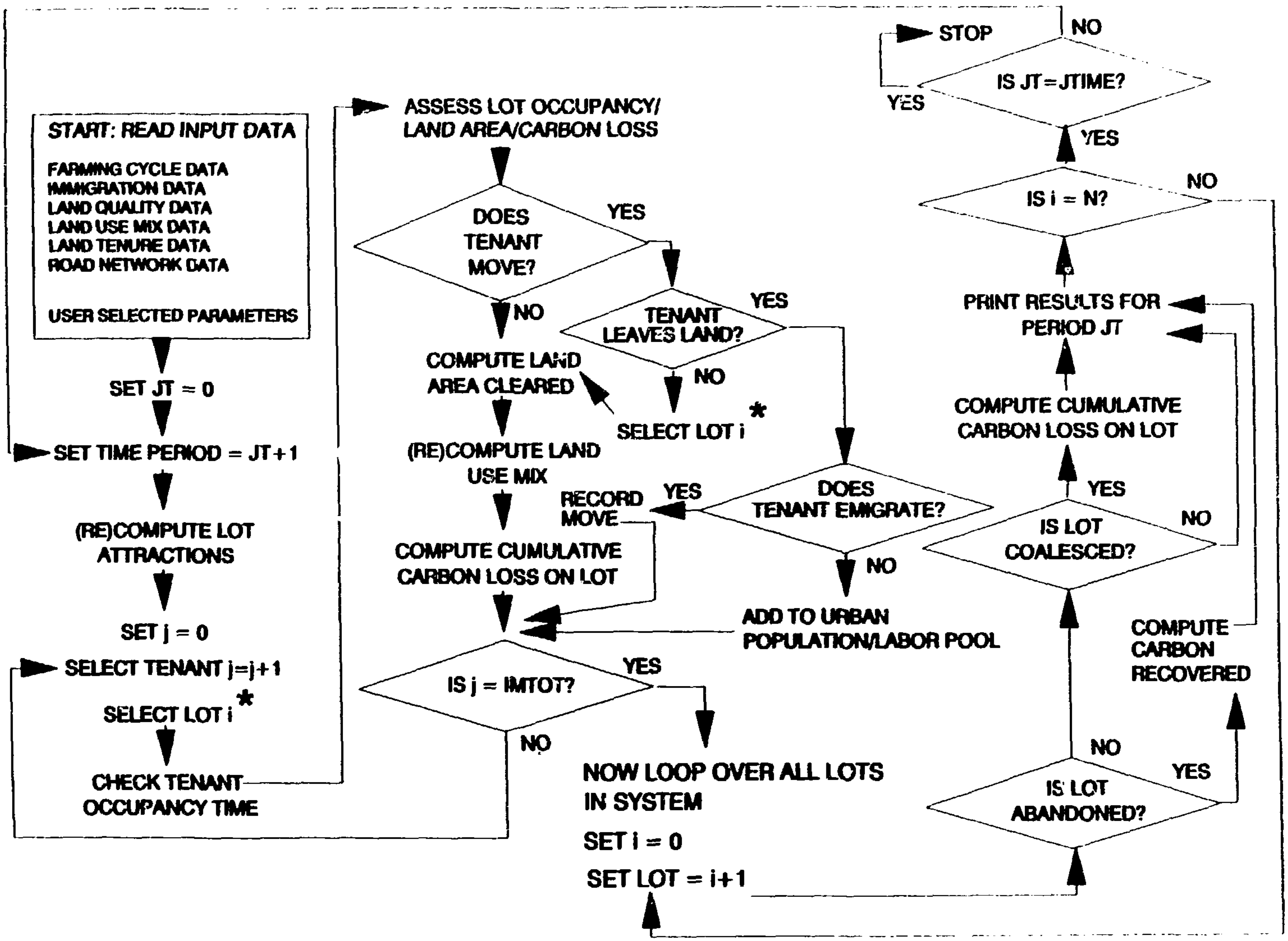
Figure 8. Map of percent deforestation for the scenario with lot size weighted most heavily.

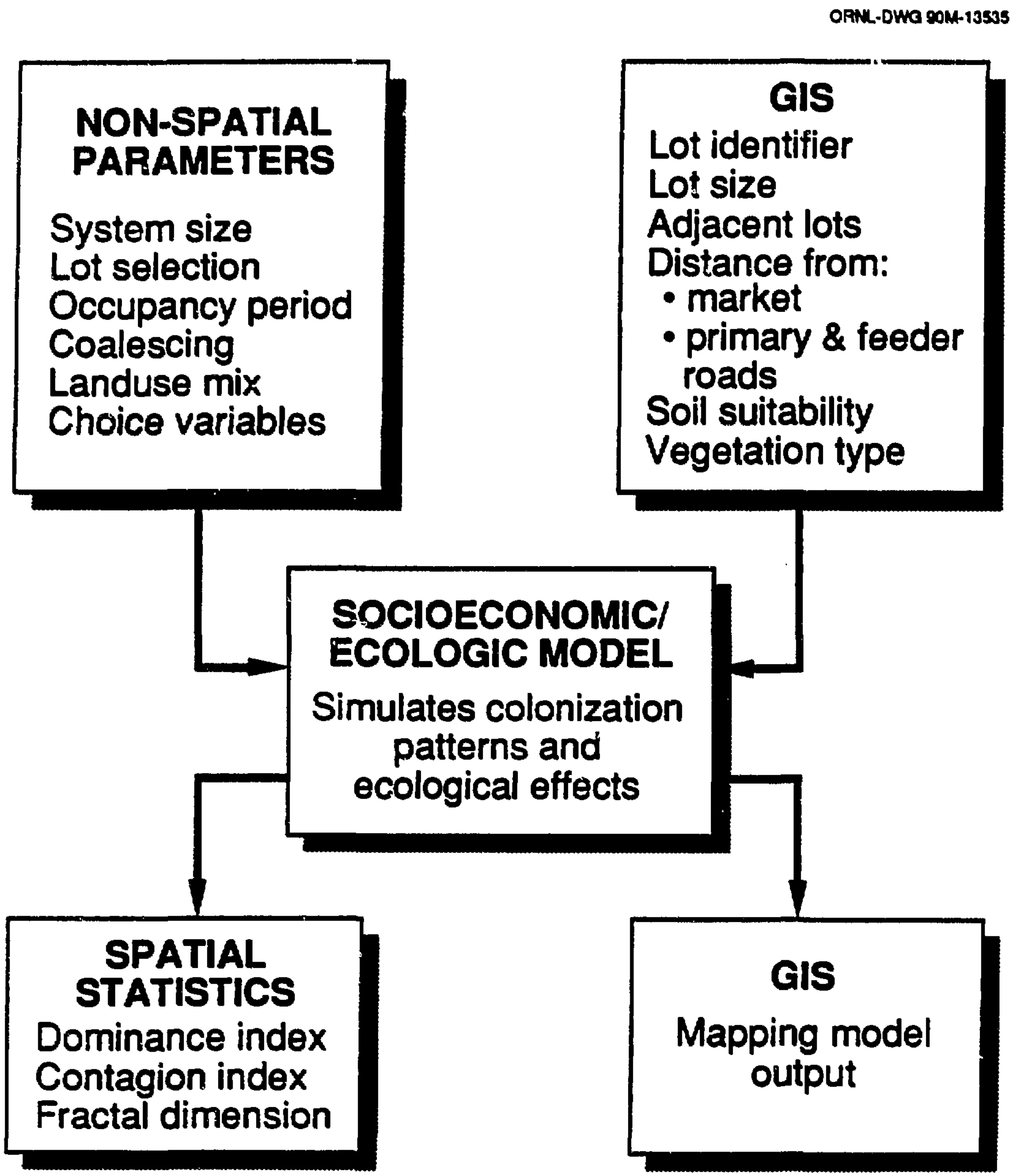
Figure 9. Dominance for the three scenarios.

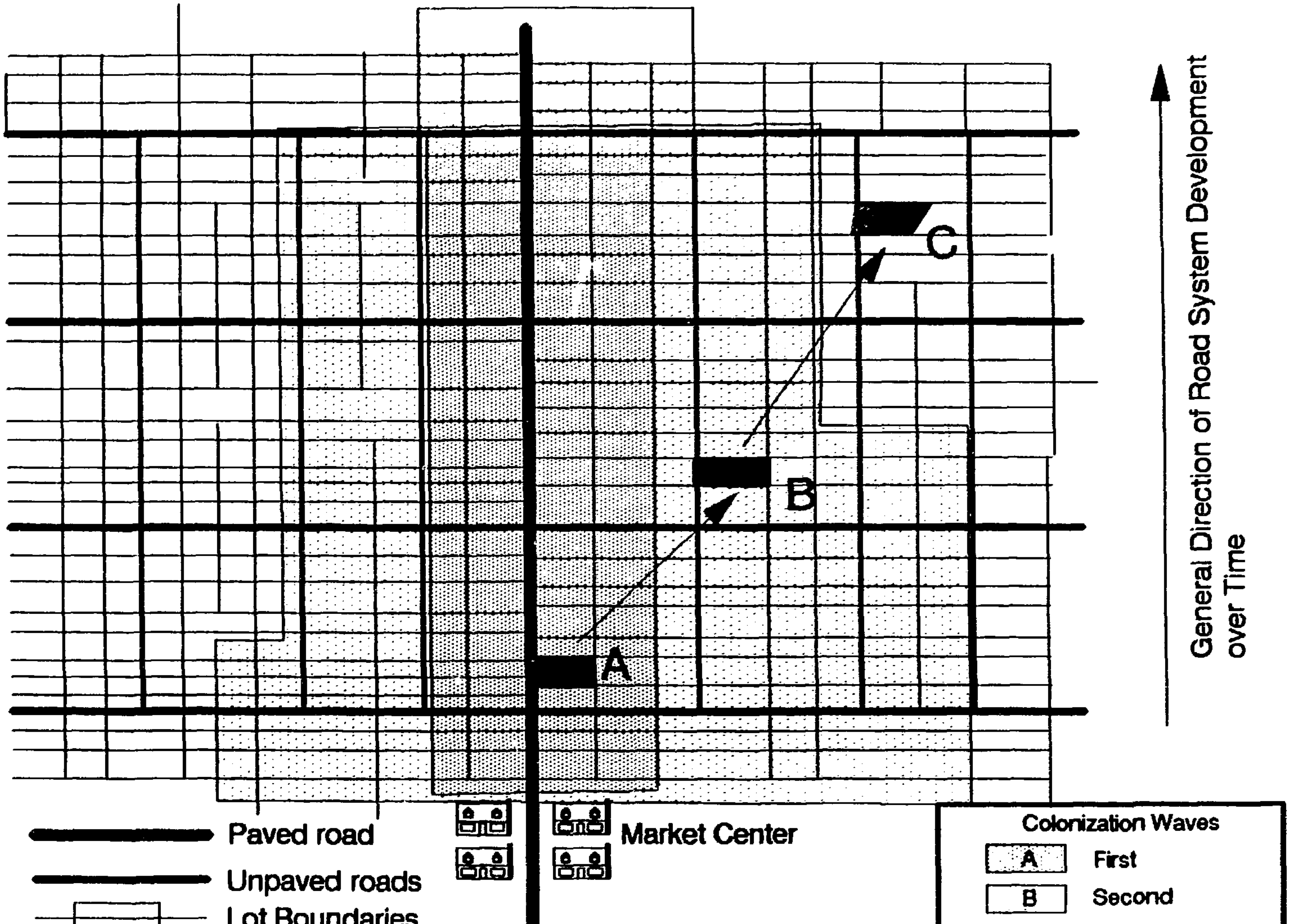
Figure 10. Contagion for the three scenarios.

Figure 11. Fractal dimension of the three scenarios (for clusters of a size four or larger).

Figure 1. Flowchart of major computational steps in DELTA

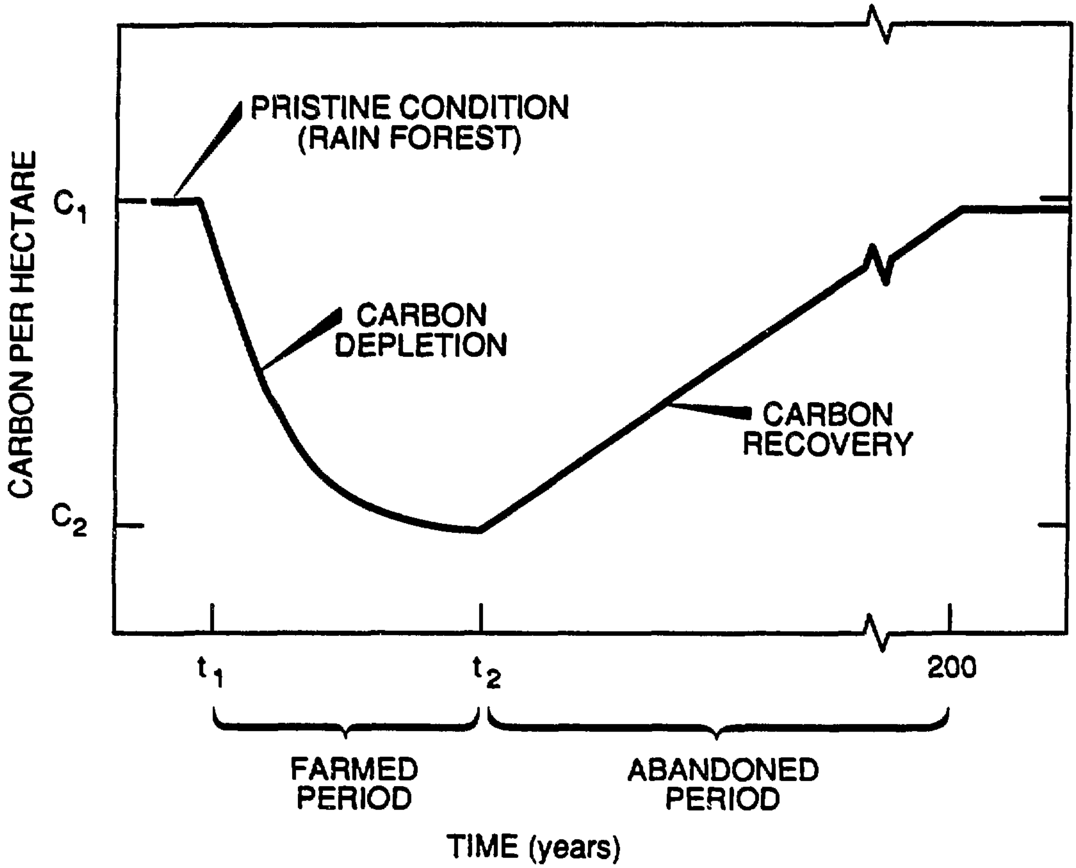



ORNL-DWG 90M-13535
NON-SPATIAL PARAMETERS
System size
Lot selection
Occupancy period
Coalescing
Landuse mix
Choice variables
GIS
Lot identifier
Lot size
Adjacent lots
Distance from:
• market
• primary & feeder roads
Soil suitability
Vegetation type
SOCIOECONOMIC/ ECOLOGIC MODEL
Simulates colonization patterns and ecological effects
SPATIAL STATISTICS
Dominance index
Contagion index
Fractal dimension
GIS
Mapping model output

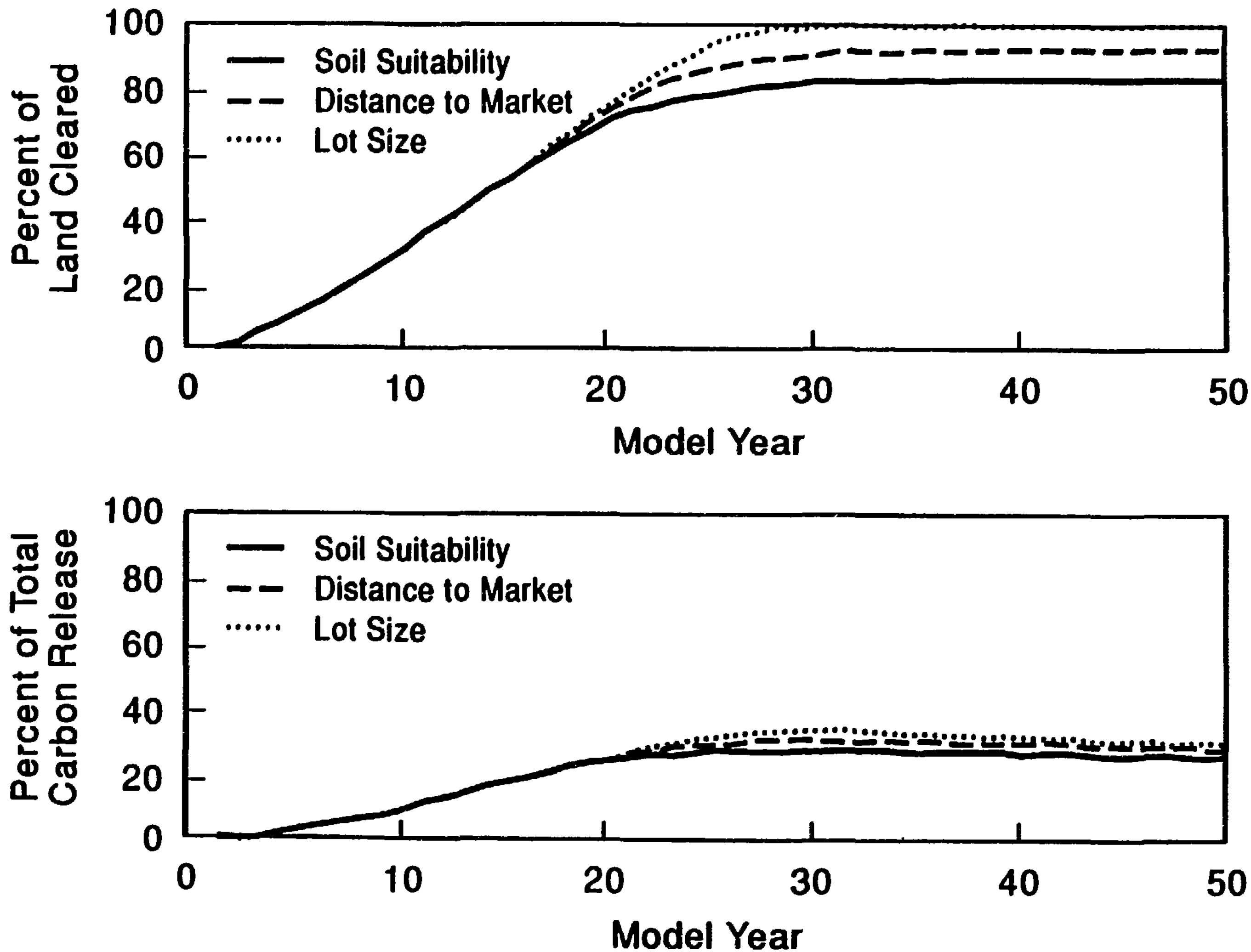


A
B
C
General Direction of Road System Development over Time
Paved road
Unpaved roads
Lot Boundaries
Market Center
Colonization Waves
A First
B Second
C Third

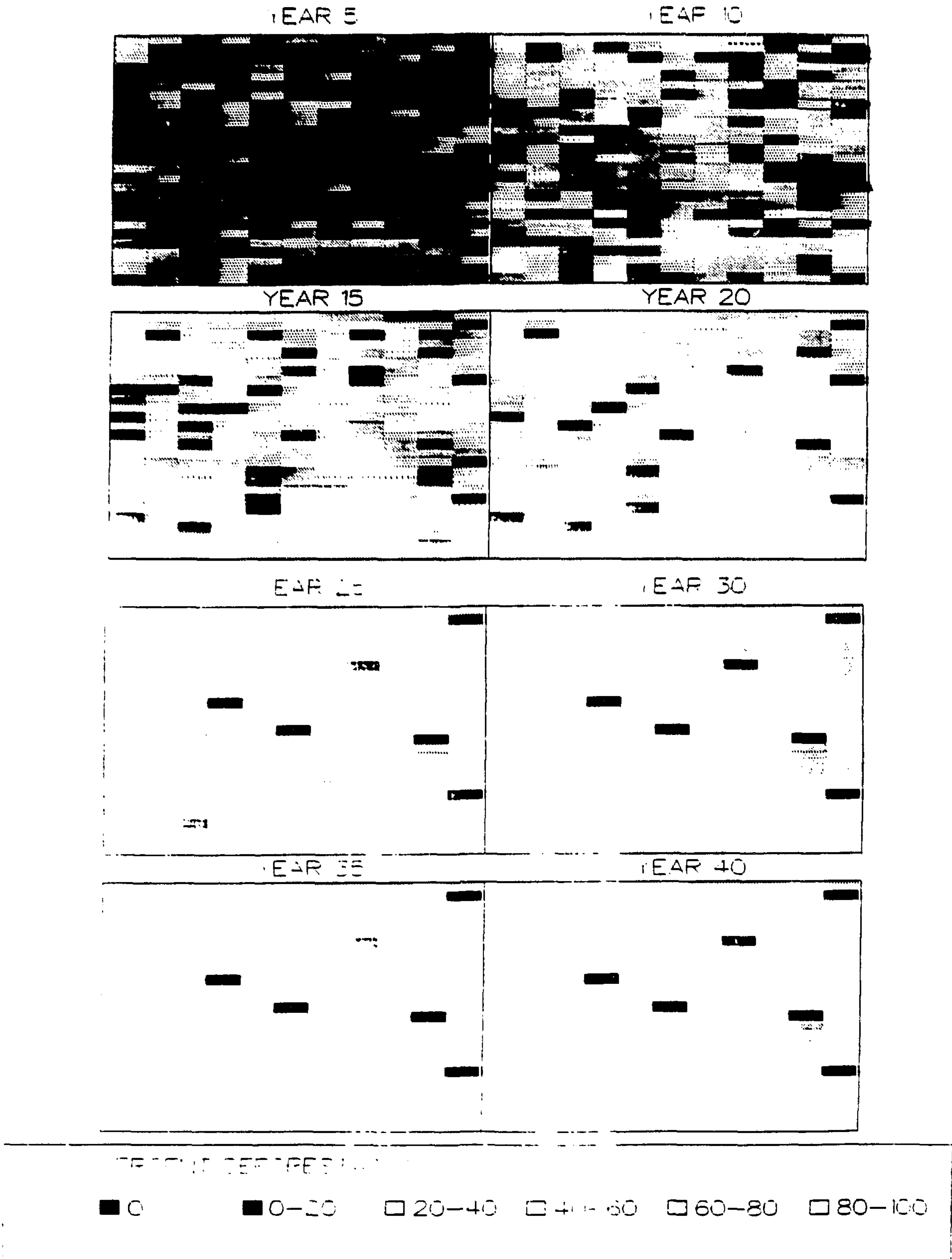
ORNL-DWG 90M-13772



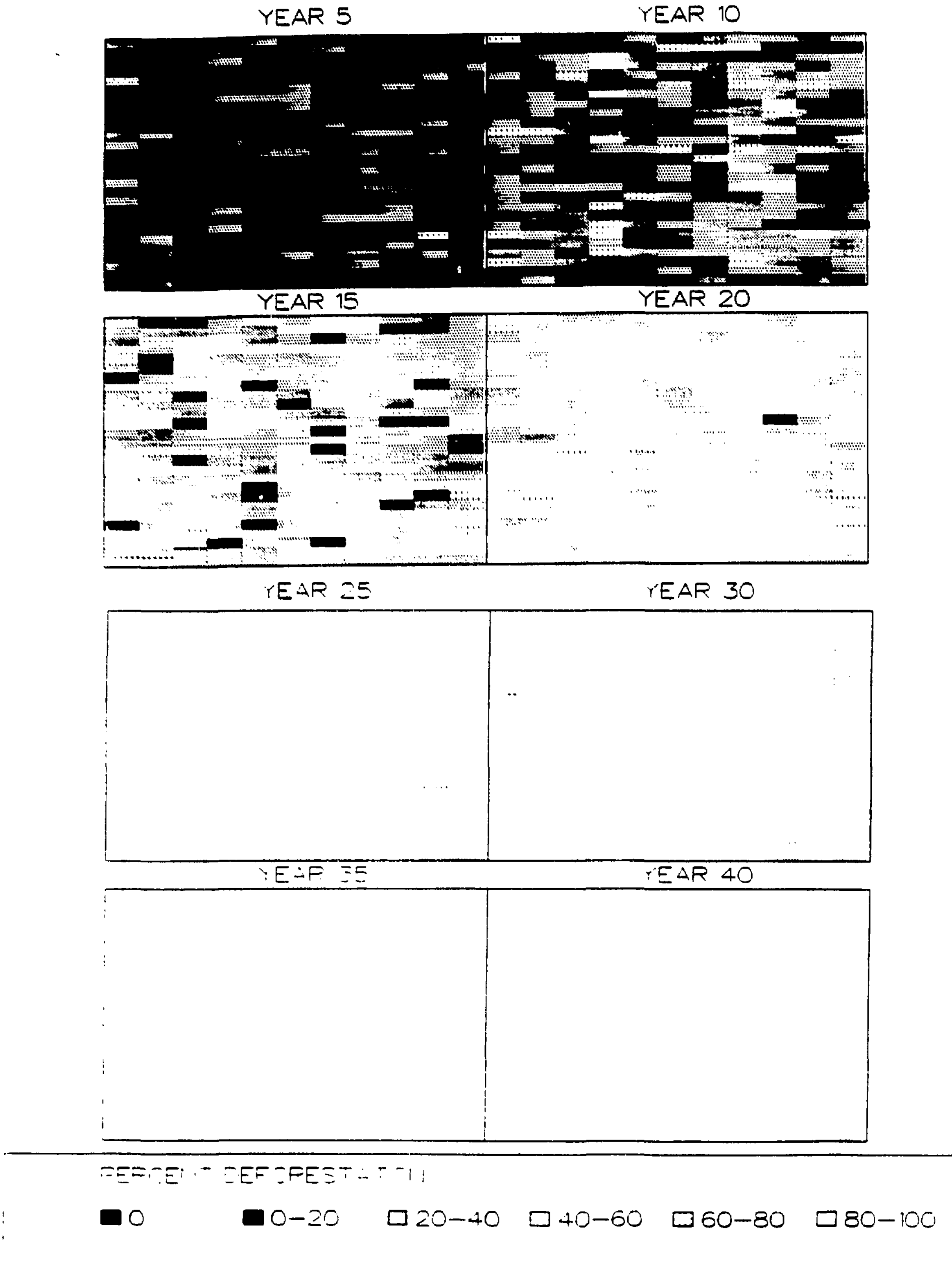
ORNL DWG 91Z-13019



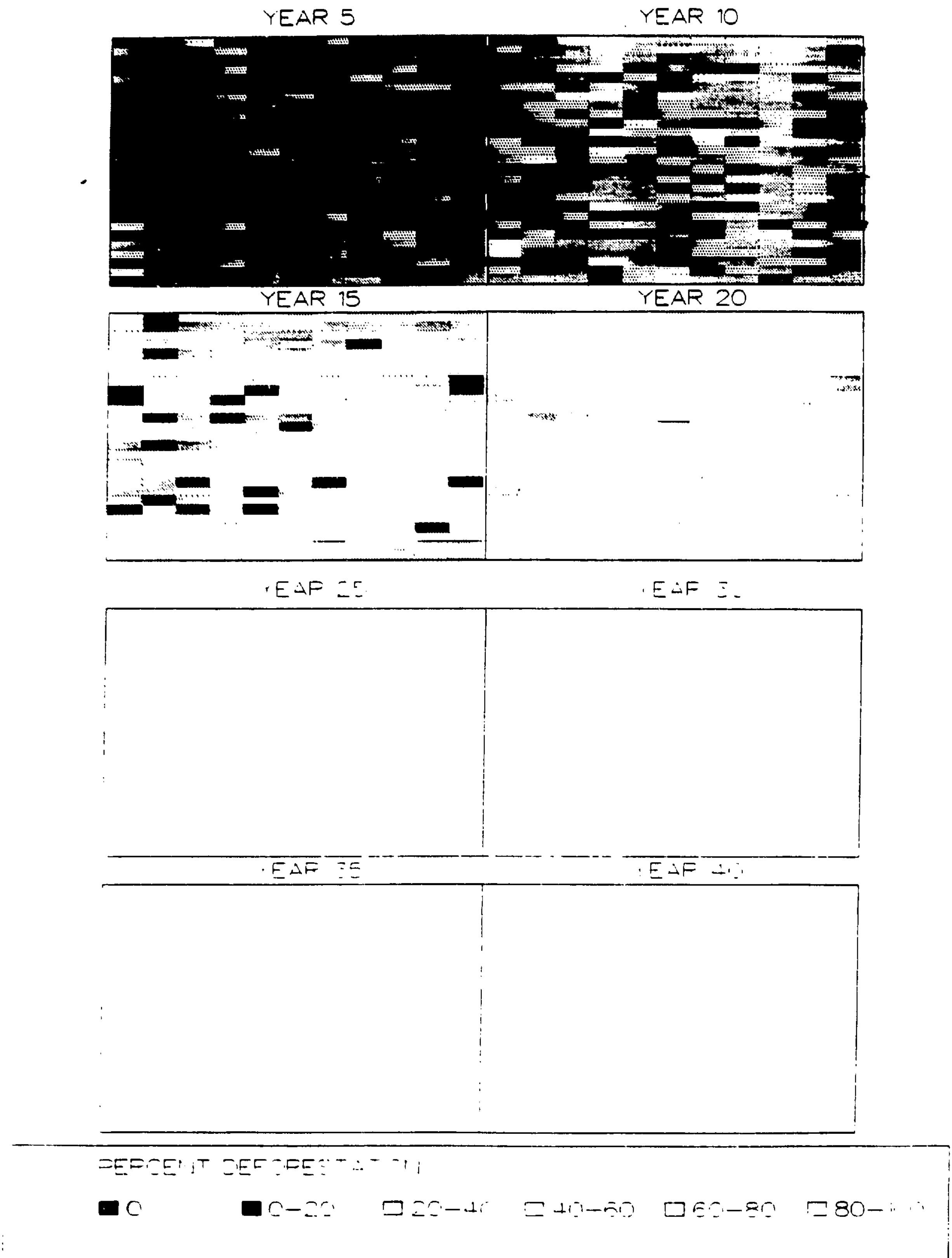
Factor Weighted: Soil Suitability



Factor Weighted: Distance to Market

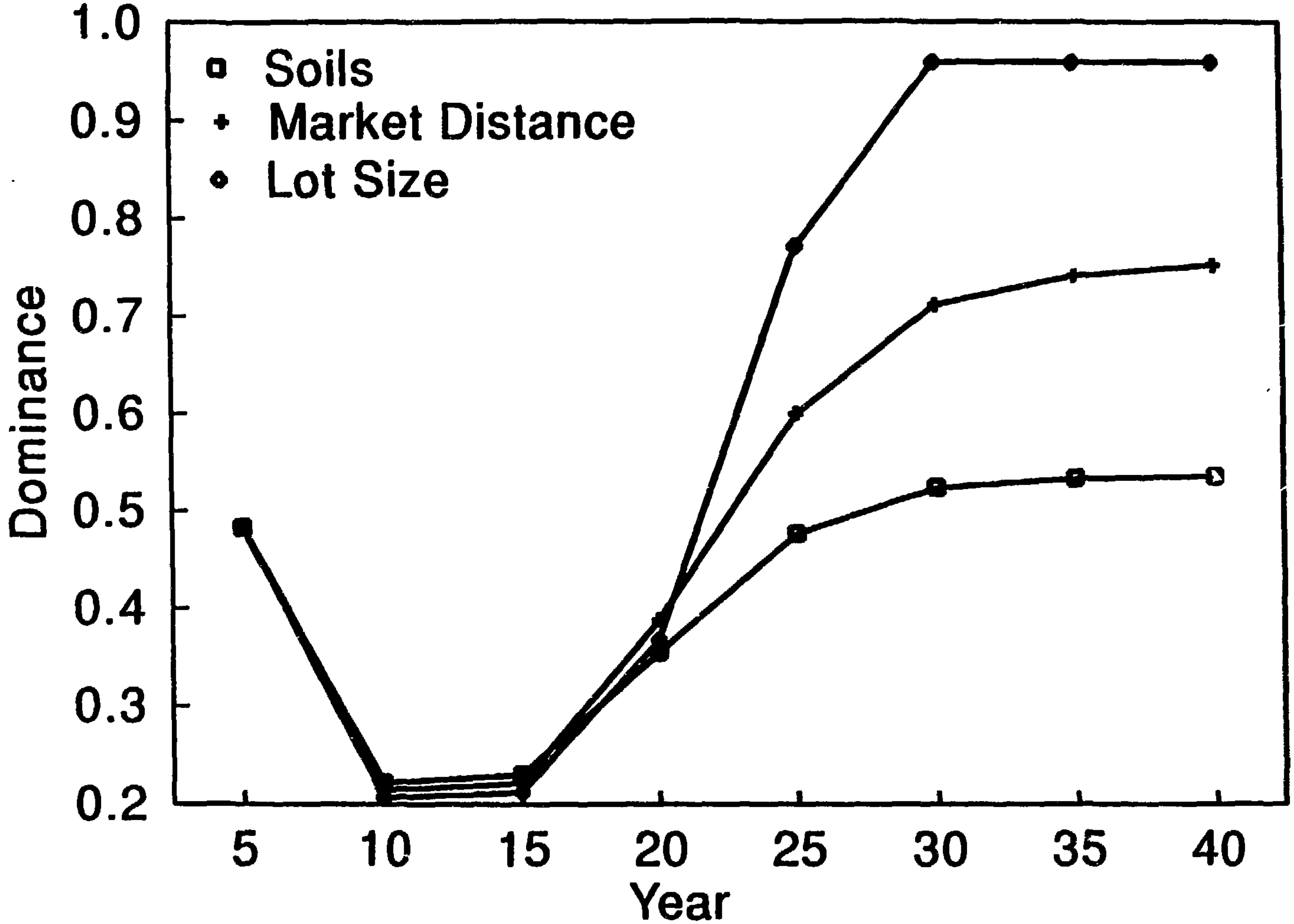


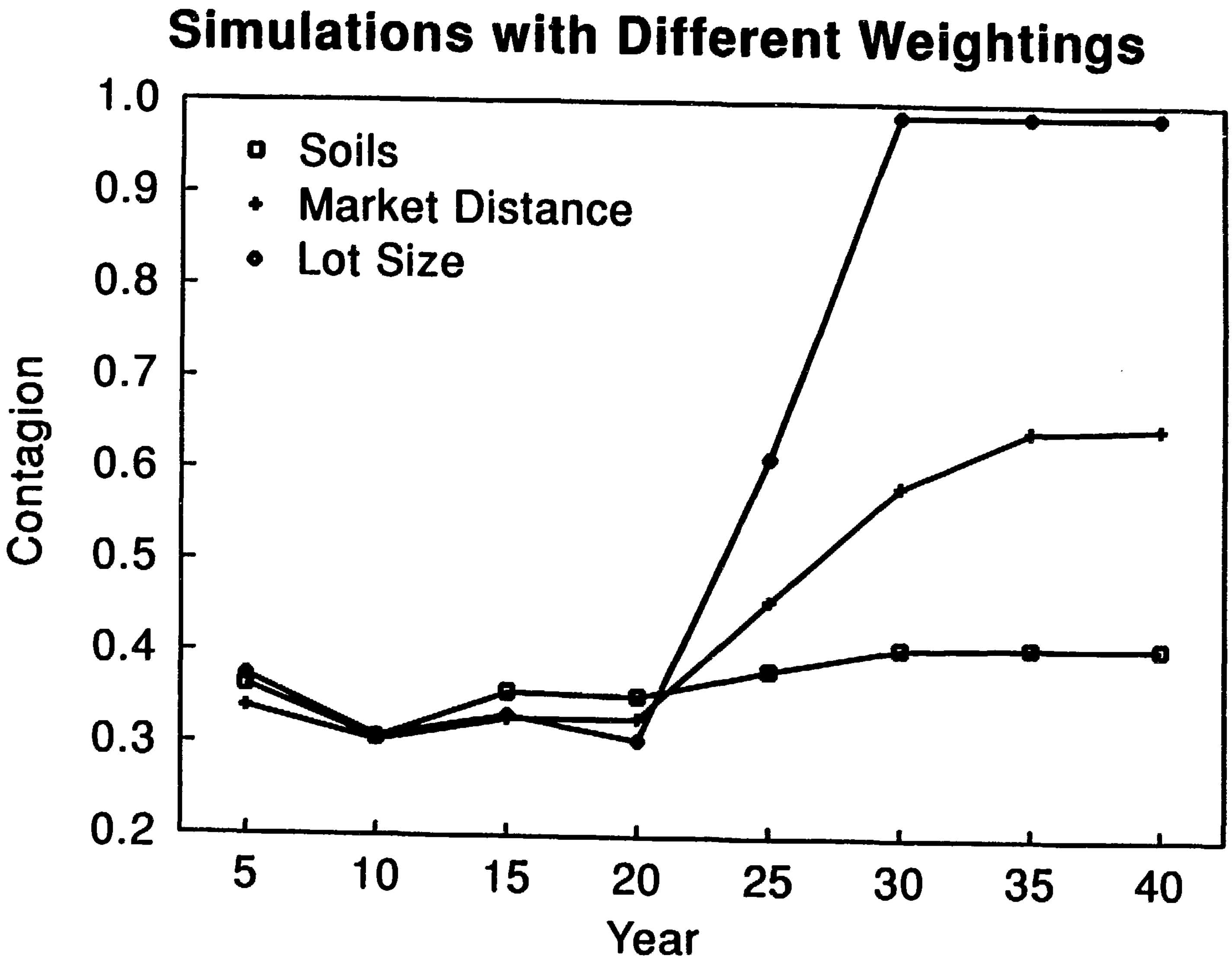
Factor Weighted: Lot Size



ORNL-DGW 91Z-13011

Simulations with Different Weightings




Simulations with Different Weightings
Soils
Market Distance
Lot Size
Contagion
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
5
10
15
20
25
30
35
40
Year

ORNL-DWG 91Z-13014