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Modeling the spatial pattern of land-use change with GEOMOD2: application and validation for Costa Rica

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Abstract

The objective of this paper is to simulate the location of land-use change, specifically forest disturbance, in Costa Rica over several decades. This paper presents a GIS-based model, GEOMOD2, which quantifies factors associated with land-use, and simulates the spatial pattern of land-use forward and backward in time. GEOMOD2 reads rasterized maps of land-use and other biogeophysical attributes to determine empirically the attributes of land that humans tend to use. Then GEOMOD2 uses the patterns of those biogeophysical attributes to simulate the spatial pattern of land-use change. GEOMOD2 can select locations for land-use change according to any of three decision rules based on (1) nearest neighbors, (2) stratification by political sub-region, and/or (3) the pattern of biogeophysical attributes. GEOMOD2 simulates the progressive loss of closed-canopy forest in Costa Rica for 1940, 1961 and 1983, which are the years for which maps of land-use are available. Also, GEOMOD2 extrapolates the pattern of land-use to the year 2010. When GEOMOD2 extrapolates land-use change over several decades, it is able to classify correctly between 74 and 88% of the grid cells, for two categories: forest versus non-forest. Over various simulation runs, Kappa ranges from 0.31 to 0.53. The model's ability to predict the location of disturbance is best when the model is driven by the location of biogeophysical characteristics, most importantly lifezones.

Keywords: GEOMOD; Kappa; Land-use; GIS model; Simulation; Validation

1. Introduction

In spite of strong conservation efforts, Costa Rica is being deforested at a rate of more than 2% per year (WRI, 1994). A contributing factor to this high rate is Costa Rica's policy to increase exports of agricultural and timber products (Hansen-Kuhn, 1993). But even if Costa Rica were to use its land to raise only food crops for domestic consumption, it is unlikely that Costa Rica could become self sufficient in food by the middle of the 21st century because Costa Rica's population growth rate is about 2.6% per year and its most productive land is already used heavily (Hall and Hall, 1993). Hall (2000) discusses the potential for Costa Rica to raise yields through technological change. However, in many locations new technology is applied to land of decreasing quality, thus only neutralizing land degradation. Therefore, if Costa Ricans attempt to feed themselves, it is likely that much of the remaining forests will be disturbed in the near future.

This is of great concern to environmentalists because an increase in the disturbance of the biotically diverse forests in Costa Rica could cause many species to go extinct. Such deforestation would also continue to cause greenhouse gasses to be released to the atmosphere, despite considerable efforts by Costa Rica to sequester carbon through forest protection and planting. For example, in 1987, the per capita release of

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carbon dioxide from Costa Rica was more than three times the world average, and 95% of the carbon release from Costa Rica was attributed to land-use change (WRI, 1990). Therefore, if computer models that predict the location of land-use change are developed further, they could help scientists and policy makers to understand, anticipate and possibly prevent the adverse effects of land-use change, by focusing policies on those locations that are most threatened (Meyer and Turner, 1992; Turner et al., 1993). Furthermore, if models can simulate backwards in time, thus construct maps of historical land-use for times where empirical maps do not exist, then they can help scientists link past land-use change to historical data on carbon dioxide release, species presence and nutrient budgets.

Lambin (1994) and Kaimowitz and Angelsen (1998) supply an extensive review of such tropical deforestation models. For some models, validation is getting underway (Veldkamp and Fresco, 1996; Verburg et al., 1999; Kok et al., this issue), however it is difficult to validate many of these models because data are usually not available over long periods of time, especially for tropical landscapes. This paper assesses the validity of the spatial component of a GIS-based model, GEOMOD2, which simulates the pattern of land-use forward and backward in time. GEOMOD2 is applied to Costa Rica, then GEOMOD2's simulation results are compared with maps of the actual distribution of closed-canopy forest for the years 1940, 1961 and 1983. An additional goal of this research is to create a land-use change model that can be used in other parts of the world. Therefore GEOMOD2 has been designed to be sufficiently robust to use in future research in regions where the availability of maps is unknown.

2. Methods

GEOMOD2 uses digital raster maps of biogeophysical attributes, as well as digital maps of existing land-use, to extrapolate the known pattern of land-use from one point in time to other points in time. GEOMOD2 is an empirical version of GEOMOD1, which used elevation and slope to simulate land-use change in tropical Asia (Hall et al., 1995a,b). Fig. 1 shows the loop and subroutine structure of the code, which is in FORTRAN.

2.1. The data

Forest maps, adapted from Sader and Joyce (1988), serve as the empirical land-use maps for three points in time: 1940, 1961 and 1983. Each grid cell in these maps represents land that either has 80% or more crown cover or has less than 80% crown cover. Those areas with 80% or more crown cover are considered relatively "undisturbed" closed-canopy forests, while those areas that have lost some or all of their crown cover is considered relatively "disturbed". These maps show a progressive expansion of human disturbance across the Costa Rican landscape, and are used as an indicator of the location of land-use change over time. According to Sader and Joyce (1988), land that has been disturbed usually does not return to closed-canopy forest. Land that is abandoned by humans may return to a more natural state, as in northwestern Costa Rica. But the recovery is rarely complete, so the land-use maps show uni-directional loss of closed-canopy forests over time. Therefore, in this study, "undisturbed" means closed-cover forest that has not been disturbed in the recent past. Thus, in GEOMOD2's simulation forward in time, only closed-canopy forest grid cells are candidates for conversion, and in the simulation backward in time, only disturbed grid cells are candidates for conversion.

The maps of closed cover forest were digitized directly from the image in Sader and Joyce. This was necessary because the original digital files had been destroyed (Sader, personal communication). The grid cell size and outer edge was manipulated to fit the other maps of physical attributes described next.

For the application to Costa Rica, GEOMOD2 uses maps of six attributes: lifezone, elevation, soil moisture, soil type, precipitation, and potential land-use. These attributes are available, are likely to affect the way humans use land, and are relatively stable over time. It is important that they are stable over time because the goal is to project land-use forward and backward from one point in time.

Fig. 2 shows the map of lifezones (Holdridge, 1948; Holdridge et al., 1971), which was digitized from a paper map (Tosi, 1969). It has 19 different lifezone categories that synthesize several climatic factors. The other attribute maps were digitized from a series of paper maps produced by the Agency for International Development and the US Army Corps of Engineers

```
Subroutine READER:       read parameters and maps
Subroutine INITIAL:      initialize variables
Subroutine FRICT:        create suitability map

BEGIN TIME LOOP
Subroutine NEWERA:       read land-use change rates

    BEGIN SUB-REGION LOOP
    Subroutine CONVERT:      compute # of grid cells to convert
    Subroutine WHERE:        use latitude and longitude loops to
                             select location of grid cells to
                             convert

        BEGIN LATITUDE LOOP
        search rows of map
            BEGIN LONGITUDE LOOP
            search columns of map
            1)      if using nearest-neighbor rule, then
                    restrict search to grid cells that
                    are on the border between non-disturbed
                    and disturbed areas
            2)      if simulating forward in time, then
                    mark non-disturbed grid cells, and
                    if using attribute rule also, then
                    mark only the non-disturbed grid cell that
                    has maximum available suitability value
            3)      if simulating backward in time, then
                    mark disturbed grid cells, and
                    if using attribute rule also, then
                    mark only the disturbed grid cell that
                    has minimum available suitability value
            END LONGITUDE LOOP
        END LATITUDE LOOP

    Subroutine FLUX:         convert marked grid cell(s) and
                             if desired, compute carbon flux
    END SUB-REGION LOOP

Subroutine WRITER:       compute success rate and write output
END TIME LOOP
```

Fig. 1. Outline of FORTRAN code for GEOMOD2.

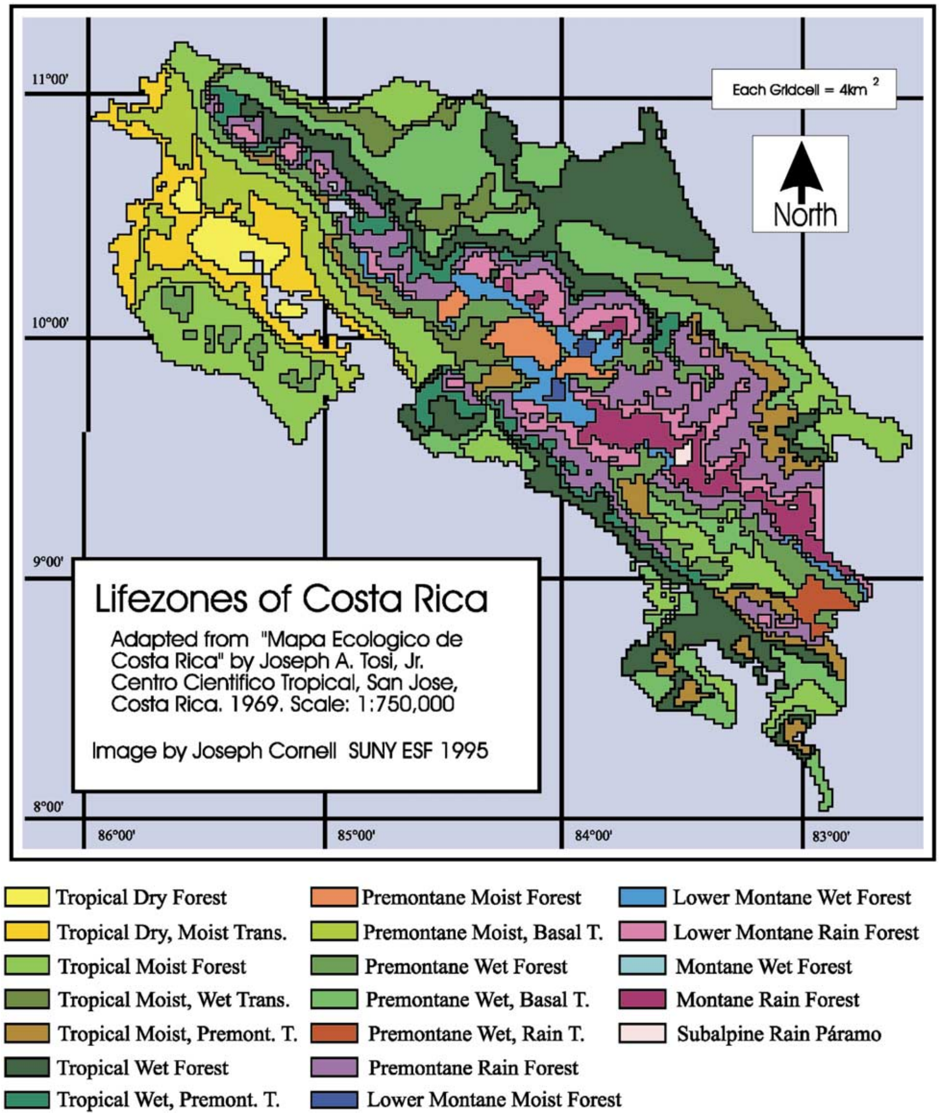


Fig. 2. Map of lifezones.

(US Army, 1965). The number of categories in each map is 10 for elevation, eight for soil moisture, 14 for soil type, nine for precipitation, and 20 for potential land-use.

The soil type map includes in order of prominence: Lithosols, Latosols, Planosols, Andosols and Regosols, Low-Humic Gley Soils, Alluvial Soils, Grumusols, and a mixed category. The Alluvial Soils, Andosols and Regosols, and Latosols are subdivided further by topography. Each category of the potential land-use map is a combination of: one of two moisture levels (dry or humid), one of three temperature levels (tropical, subtropical or cool), one of two yield levels (high or medium), one of two crop types (perennial or annual). In addition there are three other categories: hardwoods, mangroves and extensive agriculture. In all the digital raster maps, each grid cell represents an area 2 km × 2 km.

2.2. The model

GEOMOD2 selects the locations of land to be converted according to three decision rules. At the discretion of the user, any of the three decision rules can be either included or excluded.

The first decision rule is based on the nearest neighbor principle, whereby, in any one time step, GEOMOD2 restricts land-use conversion to those areas that are on the border between closed-canopy forest and disturbed land. This rule simulates the manner in which newly disturbed land grows out of previously disturbed land.

The second decision rule concerns sub-regional stratification. GEOMOD2 can specify the annual amount of land-use change within a series of sub-regions, which are provinces in the case of Costa Rica. It is possible to have any regional stratification for which data exist. For example, planning regions would also be a good choice.

The third decision rule concerns biogeophysical attributes. Under this third rule, GEOMOD2 predicts future disturbance at locations that have attributes that are similar to the attributes of previously disturbed areas. To incorporate this rule into the model, GEOMOD2 creates a "suitability" map empirically, by using several attribute maps and one land-use map. The suitability map has high values at locations that have biogeophysical attributes similar to those of disturbed land, and has low values at locations that have biogeophysical attributes similar to those of undisturbed closed-cover forest. GEOMOD2 simulates future disturbance by searching the landscape for the location that has the highest available suitability value.

The suitability map is created in two steps. First, GEOMOD2 reclassifies each attribute map such that the grid cells of each category of the attribute map are assigned a percent-disturbed value, obtained by comparing the attribute map to the initial land-use map. The percent-disturbed value of each category in the attribute map is computed as the ratio of the quantity of disturbed grid cells of that category to the quantity of all grid cells of that category. For example, Fig. 3 shows the information necessary to compute percent-disturbed for each category in the lifezone map.

After each attribute map is thus reclassified, GEOMOD2 creates the suitability map by computing for each grid cell a weighted sum of all the reclassified attribute maps. Hence, the suitability in each cell is calculated according to the following:

$$R(i) = \sum_{a=1}^{A} W_a P_a(i) \tag{1}$$

where $R(i)$ is the suitability value in cell (i), a the particular geophysical attribute map, A the number of geophysical attribute maps, W_a the weight of geophysical attribute map a, and $P_a(i)$ the percent-disturbed in category a_k of attribute map a, where cell (i) is a member of category a_k.

The weight for each attribute reflects the correlation between the attribute and disturbance. The weight is proportional to the attribute's coefficient in the first principal component of all reclassified attributes. The first principal component is calculated using the covariance matrix, as opposed to the correlation matrix, because each reclassified attribute is on the same scale, 0–100%. Fig. 4 gives the weights for each of the attributes for five different time periods of initial information. Three of these time periods are 1940, 1961 and 1983. The other two, 1940–1961 and 1961–1983, result from an alternative method to compute percent-disturbed.

In this alternative method, the suitability map is constructed from the attribute maps and two empirical land-use maps from different points in time (as opposed to only one land-use map). The two empirical land-use maps are used to determine which land has experienced land-use change between the two points in time. In Eq. (1), $P_a(i)$ would equal the percent of grid cells disturbed in category a_k that undergo land-use change during the time interval between the two empirical maps, where cell (i) is a member of category a_k.

While using this alternative method for the simulation from 1961 to 1983, the two empirical land-use maps would be 1940 and 1961. The simulation proceeds from 1961 to 1983, where the results are subject to validation.

2.3. Quantity of disturbance

The number of grid cells of land-use change per year in each region is determined by linear interpolation of the area of forest cover in the empirical maps of 1940,

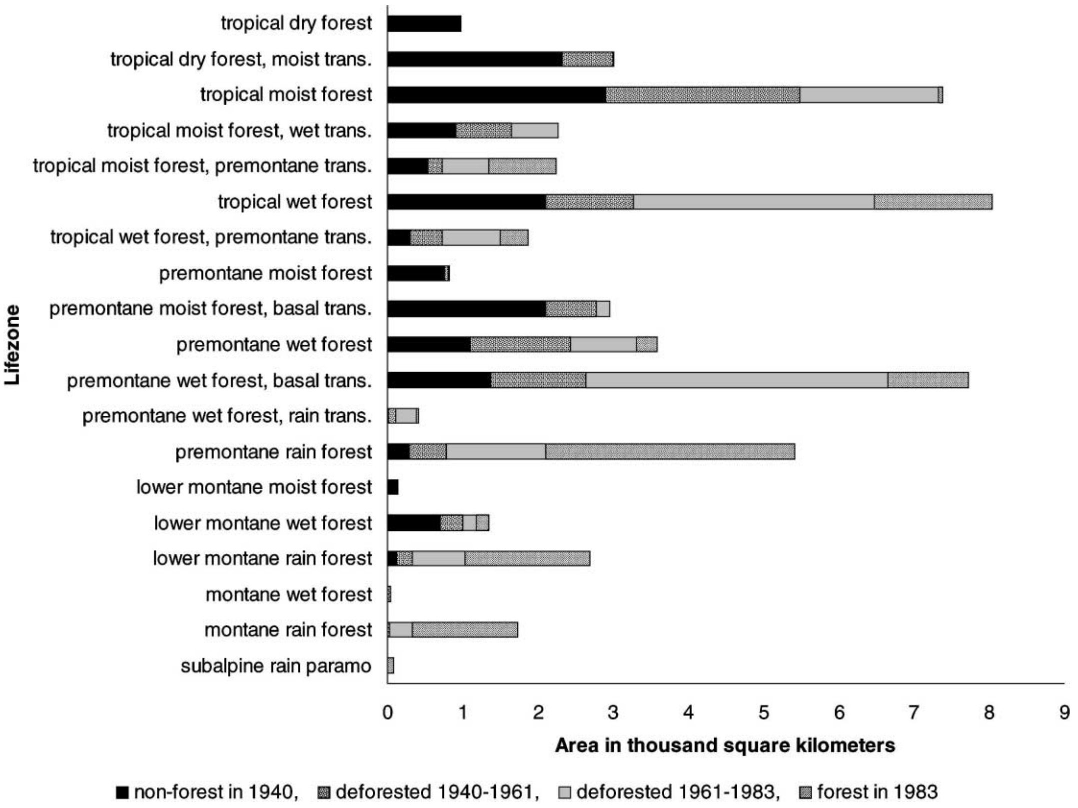


Fig. 3. Time interval that each portion of each lifezone became disturbed.

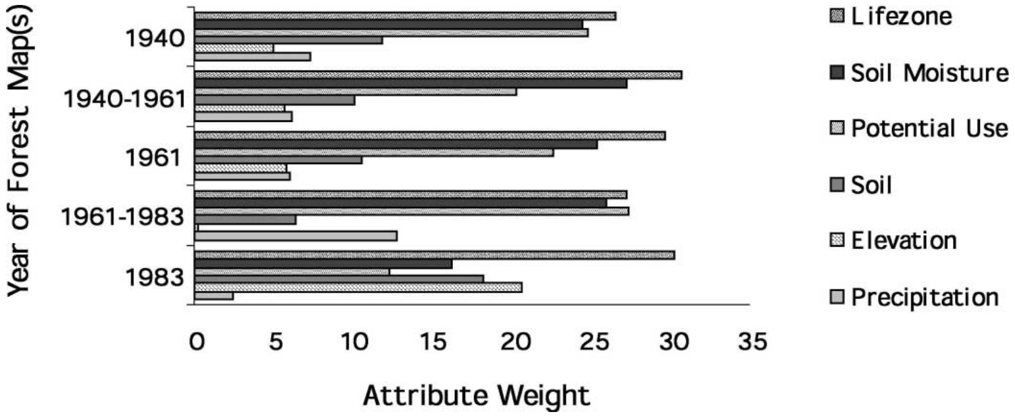


Fig. 4. Attribute weights. The weight for each attribute reflects the correlation between the attribute and percent-disturbed. The weight is proportional to the attribute's coefficient in the first principal component of all reclassified attributes. Attributes that are highly correlated with disturbance receive relatively large weights, and attributes that are less correlated with disturbance receive smaller weights.

Table 1
Annual rate of disturbance to closed-canopy forest between 1961 and 1983 by region

Region	Rate (Annual %)
Guancaste	10.5
Alajuela	7.1
Heredia	3.2
Limon	2.1
Puntarenas	4.9
San Jose	4.0
Cartago	0.8
Total	3.9

1961 and 1983. Thus, GEOMOD2 simulates only the pattern of land-use change, not the quantity of change.

For the simulation to 2010, the quantity of future closed-canopy forest is determined by extrapolating for each province an exponential decay curve through the years 1961 and 1983. Table 1 gives the rates implied by the maps. This decay relationship was chosen based on the relationship observed for the quantity of tropical deforestation over long periods of time (Richards and Flint, 1994). It is also based on the idea that as the amount of remaining forest becomes smaller, the amount of additional deforestation per year slows, due to efforts to preserve the remaining forest and declining quality of remaining land. The predictive power of the simulation could be improved with better estimates on the future quantity of change in Costa Rica, however the purpose of GEOMOD2 is to simulate the pattern of change, not the quantity of change.

2.4. Validation

The method of validation is first to read digital maps of empirical land-use for 1940, 1961 and 1983, then to use an empirical map for a single year to derive a simulated map for a different year, then to compare the simulated map to the empirical map for the simulated year. A "success" occurs when a grid cell in the map of simulated land-use matches the corresponding grid cell in the map of empirical land-use.

The Kappa parameter compares GEOMOD2's percent success to the expected percent success due to chance alone. It is important to use Kappa to evaluate the effectiveness of the simulation, because the percent success due to random chance can be substantial, due in part to the fact that the model cheats by specifying the correct quantity of deforestation. Kappa administers appropriate punishment for cheating on the quantity of deforestation.

$$\text{Kappa} = \frac{P_{\text{o}} - P_{\text{c}}}{P_{\text{p}} - P_{\text{c}}} \tag{2}$$

Eq. (2) gives the value of Kappa, where P_{o} is the percent correct for GEOMOD2's output, P_{c} the expected correct due to chance, and P_{p} the percent correct when classification is perfect, which is 100%.

2.5. Analysis of decision rules

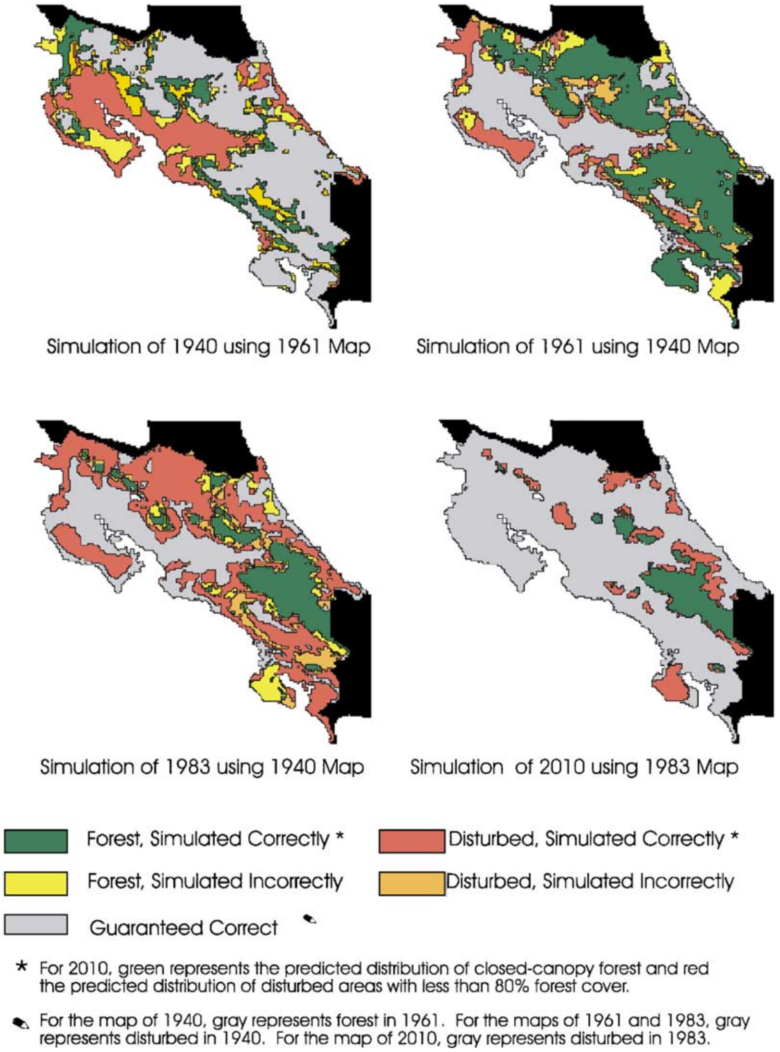
The effects of GEOMOD2's three decision rules are examined by running the simulation for each possible combination of the rules. This method can determine which of the three rules (nearest neighbor, stratification, or attributes) is the most effective, and can show how Kappa varies depending on which rules are used. In each run, each rule is either on or off.

Also, the model is tested for it sensitivity to the weights W_a in Eq. (1). The model is run once for each combination of attribute weights, where the weights are either 0 or 1. These runs can show which single attribute map is the best to use, and whether it is beneficial to use several attribute maps as opposed to just one attribute map.

3. Results

Fig. 5 shows maps of the simulations that use all three decision rules, calibrated from one point in time. For the first three maps, the red and green grid cells are GEOMOD2's successes, and the orange and yellow grid cells are failures. For the map of simulated land-use of 2010, red represents simulated disturbance, and green represents simulated closed-canopy forest.

When GEOMOD2 uses all three decision rules in Costa Rica, it is able to classify correctly between 84 and 86% of the grid cells (Table 2). Specifically, when the 1940 map is simulated starting from the empirical map of 1961, the success is 84% (Kappa = 0.34), when the 1961 map is simulated starting from 1940, the success is 85% (Kappa = 0.45), and when the


Simulation of 1940 using 1961 Map

Simulation of 1961 using 1940 Map

Simulation of 1983 using 1940 Map

Simulation of 2010 using 1983 Map

* For 2010, green represents the predicted distribution of closed-canopy forest and red the predicted distribution of disturbed areas with less than 80% forest cover.

For the map of 1940, gray represents forest in 1961. For the maps of 1961 and 1983, gray represents disturbed in 1940. For the map of 2010, gray represents disturbed in 1983.

Fig. 5. Maps of simulation of 1940, 1961, 1983 and 2010.

1983 map is simulated from 1940, the success is 86% (Kappa = 0.53).

Table 2 shows also the results concerning the analysis of the two alternatives for construction of the suitability map. There are neither systematic nor substantial differences in percent success of the simulation based on land-use at one point in time versus the simulation based on land-use change between two points in time. All of these alternative simulations use all three decision rules.

The lifezones that tend to have the highest percent-disturbed are dry forests; and the lifezones that tend to have the lowest percent disturbance are wet forests (Fig. 3). From 1940 to 1961, lifezone, soil moisture and potential use are strongly correlated with percent disturbance, hence receive large weights, whereas soil, elevation, and precipitation receive relatively lower weights (Fig. 4). However, lifezone receives consistently larger weights from 1940 to 1983.

Lifezone tends to be the most successful single attribute when the simulations are run with only one attribute map at a time. However, the simulations that use a weighted combination of the attributes are

Table 2
Analysis showing the relative percents of success for simulations based on all three decision rules and various initial information. Each simulation uses one of two alternatives for initial information. The first alternative uses maps of attributes and land-use at one point in time. The second alternative uses maps of attributes and land-use change over two points in time

Version of attribute rule	Percentage of success		
	Chance	GEOMOD2	Kappa
Simulation of 1940			
From 1961			
Using 1961 map	76	84	0.34
Using 1961 and 1963 maps	76	84	0.33
From 1983			
Using 1983 map	62	74	0.31
Simulation of 1961			
From 1940			
Using 1940 map	72	85	0.45
From 1983			
Using 1983 map	64	78	0.40
Simulation of 1983			
From 1940			
Using 1940 map	71	86	0.53
From 1961			
Using 1961 map	76	88	0.50
Using 1940 and 1961 maps	76	88	0.51

consistently more successful than the simulations that use only the best single attribute, regardless of whether the nearest-neighbor and/or stratification rules are used. The weights based on the first principal component resulted in more successful simulations than the combinations of 0 or 1 weights.

Fig. 6 shows that simulation runs that produce the largest Kappas are the runs that use all three decision rules. The Kappa parameter can change by as much as 0.36, depending on which decision rules are used. Specifically, in predicting the 1983 map from the 1940 map, the simulation based on only the nearest neighbor rule yields a Kappa of 0.17, whereas the simulation based on all three rules yields a Kappa of 0.53. Fig. 6 shows also that the single most effective decision rule is the one based on the attribute maps, and that the sub-regional stratification rule always increases the success of the simulation, regardless of which other rules are included.

4. Discussion

4.1. Location of errors

Fig. 5 shows the location of GEOMOD2's successes and errors. Analysis of the locations of GEOMOD2's errors indicates that the simulation could be improved by taking into consideration the network of protected areas. In the simulation of 1983 using the 1940 map, GEOMOD2 shows simulated disturbance on the Osa Peninsula in southwestern Costa Rica, however there is no disturbance in the empirical map of 1983. The reason is that land on the Osa Peninsula is protected, even though it has attributes that are similar to land that has been previously targeted for disturbance. This is an indication that the protected status of the Osa Peninsula has been effective in protecting that

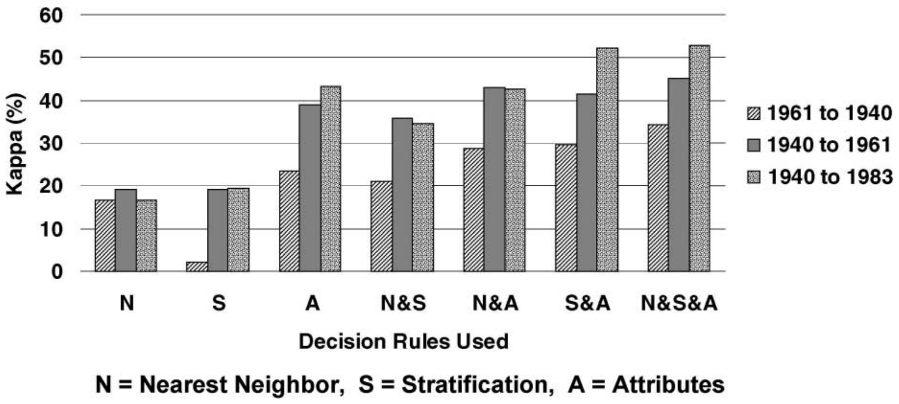


Fig. 6. Effect of decision rules on simulation of 1940 from 1961, 1961 from 1940, and 1983 from 1940.

land. Additional social factors could account for GEOMOD2's errors. Those factors are discussed below.

4.2. Model limitations

GEOMOD2 is designed to predict only the location where land-use change is likely to occur, it does not predict the quantity of land-use change. GEOMOD2 sets the amount of closed-canopy forest area in the simulated map of any particular year to be equal to the empirical (or projected) amount of closed-canopy forest area in that year. In the validation phase of the research, this procedure sets a lower bound on the simulation's percent success, and determines the expected success due to chance, which underscores the importance of using the Kappa to judge the simulation. GEOMOD2's prediction of the pattern of remaining closed-canopy forest area into the next century could be improved by using better estimates of the quantity of future forest area. Such estimates should take into consideration the interacting forces of changes in population, technology, land degradation, land recovery, and import substitution, including prices of cash crops, food crops, livestock and agricultural inputs (Hall, 2000).

A related issue is that GEOMOD2 assumes that there is no regrowth of disturbed areas. This is another reason why it is important to merge GEOMOD2 with a model that predicts the quantity of land-use change over time, including changes in grasslands. For example, many pastures have been abandoned recently in northwestern Costa Rica (Hall, personal observation). While it is too early to call most of these areas forests, they will become forests in a decade or two if they are left undisturbed. Hence for GEOMOD2, "disturbed" is interpreted as disturbed at some time in the recent past.

4.3. Data limitations

GEOMOD2 has been designed such that it can take maximum advantage of data for the tropics, which vary highly in completeness, precision, currency, and accuracy. For example, GEOMOD2 requires only one initial land-use map. Other researchers have developed models that use maps of land-use change between two or more points in time in order to drive the pattern of change into the future (Nualchawee et al., 1981; Gastellu-Etchegorry and Sinulingga, 1988; Ludeke et al., 1990; Cornell et al., 1992; Lee et al., 1992; Brown et al., 1993; Liu et al., 1993). However, Table 2 shows that there is no systematic advantage when GEOMOD2 bases the analysis on the pattern of land-use at one point in time as opposed to the pattern of land-use change between two points in time.

If no attribute maps are available, GEOMOD2 can use only the nearest neighbor rule. Fig. 6 shows that the nearest neighbor rule and the attribute-based rule can perform with a similar level of success over two decades, especially if stratification is used also.

4.4. GEOMOD2's method versus alternatives

GEOMOD2 is dynamic in the respect that each year, GEOMOD2 re-computes candidates for disturbance by re-computing which grid cells neighbor disturbed cells. In addition, GEOMOD2 has the ability at any point in time to change the rate of land change and to add additional driver maps, such as roads, protected areas and other social factors.

This particular application of GEOMOD2 to Costa Rica is not dynamic in the sense that it uses drivers that do not change rapidly over time. The decision to limit the drivers to biophysical features is motivated by the need to compare simulations forward to simulations backward over several decades. Some segments of the scientific and policy communities are especially (and exclusively) interested in simulations forward in time. However, other members of the same communities are more interested in simulations backwards in time. For example, the United States Department of Energy wants to construct carbon budgets over the last century. Also, ecologists at the Marine Biological Laboratory, USA, want to construct nutrient flows as a function of land-use over the last century (Schneider and Pontius, this issue).

For this application to Costa Rica, GEOMOD2 used one set of relatively stable biophysical driver variables for all runs, in order to facilitate comparison among runs. However, in the real world, dynamic social factors play a major role in how land-use change proceeds. Deforestation is caused by humans, not lifezones. However, the model used maps of physical features, not social features. It would not make sense to use, e.g., population density of 1961 or 1983 to extrapolate back to 1940. Also, when the goal is to extrapolate from 1940 to 1983, it would be cheating to use a map of social conditions of 1961. If the simulation were to use a map of roads of 1961, the accuracy of the simulated map of 1983 would certainly increase. However, the simulation could not claim that the extrapolation was from 1940, since it would have used information from 1961.

Other models aim to capture the dynamics of social variables, and their influence on land change. For example (Irwin and Geoghegan, this issue) model land change in the Pautuxet watershed dynamically, such that the location of change in 1 year influences the probability of change in subsequent years. Irwin's model incorporates social variables such as roads and land prices. Another example is the CLUE model, which is fully integrated with a dynamic systems model to compute both quantity and location of land change (Veldkamp and Fresco, 1996).

The added complexity of these other models attempts to capture some of the important processes. This complexity allows the modelers to examine "what-if" policy scenarios. The disadvantage is that complex dynamic models tend to need more data for calibration. This is a problem in data poor areas, where the available data must be used for calibration. Hence, data are not necessarily available for validation. This is a problem because it will not be clear whether the added complexity increases accuracy, until these models are validated. Hence, it is important to create appropriate validation techniques in order to compare models and to decide what are the best ways to improve the models (Pontius, 2000; Schneider and Pontius, this issue; Kok et al., this issue).

4.5. *Extrapolation to other regions*

This is a case study, so these results for Costa Rica do not necessarily reflect the situation for other parts of the world. Specifically, the results concerning the method to construct the suitability map are based on a difference in Kappa of at most 0.23 (Table 2), and the Kappa differs by no more than 0.36 depending on which decision rule(s) are used (Fig. 6). If this level of variation is smaller than the variation over a sample of countries, or if the underlying mechanisms of land-use change in other countries are different than they are in Costa Rica, then case studies for other countries would yield different conclusions.

Sources of variation among countries could derive from differences in land-use policies. For example, the International Monetary Fund has encouraged Costa Rica to export agricultural and forest products, which induces deforestation on certain types of land (Hansen-Kuhn, 1993). But in other nations, the basic driving forces of deforestation may be very much different. For example, a substantial amount of deforestation in some parts of Brazil is caused by the demand for wood to supply fuel to newly established iron smelting industries (Treece, 1987). However, GEOMOD2 can be used to extrapolate a pattern of change based on either the existing empirical pattern, or on other specified rules that are thought to determine land-use change.

Other applications of GEOMOD2 will be conducted at different scales. When scale changes, the effect of any particular variable can shift from a local effect to a system wide effect. When a variable has a local effect, GEOMOD2 can simulate the effect in space within the study area. When the effect is system wide, the modeler must tell GEOMOD2 how the variable influences quantity of change within the study area. Pontius (2000) shows how to separate mathematically these two effects of location and quantity.

5. Conclusions

The purpose here is to create a method to simulate land-use change, and to validate the results, with a model that is flexible enough to use with a variety of maps as independent variables. GEOMOD2 accomplishes these goals.

GEOMOD2 associates biogeophysical attribute patterns with land-use patterns in Costa Rica, to extrapolate the spatial patterns of land-use over two to four decades, with 74–88% of the grid cells classified correctly, and Kappa ranging from 0.31 to 0.53. A model such as GEOMOD2, which is capable of using many kinds of spatial data, should be useful for simulating the pattern of future land-use, or the pattern of past land-use of years for which maps do not exist. Finally, GEOMOD2 can help decision makers envision future scenarios of land-use, and it is being used to help develop land-use strategies elsewhere in the tropics where a goal is to preserve biodiversity (Menon and Bawa, 1997).

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