

Modelling the conversion of Colombian lowland ecosystems since 1940: Drivers, patterns and rates

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Abstract

In biologically mega-diverse countries that are undergoing rapid human landscape transformation, it is important to understand and model the patterns of land cover change. This problem is particularly acute in Colombia, where lowland forests are being rapidly cleared for cropping and ranching. We apply a conceptual model with a nested set of a priori predictions to analyse the spatial and temporal patterns of land cover change for six 50–100 km² case study areas in lowland ecosystems of Colombia. Our analysis included soil fertility, a cost–distance function, and neighbourhood of forest and secondary vegetation cover as independent variables. Deforestation and forest regrowth are tested using logistic regression analysis and an information criterion approach to rank the models and predictor variables. The results show that: (a) overall the process of deforestation is better predicted by the full model containing all variables, while for regrowth the model containing only the auto-correlated neighbourhood terms is a better predictor; (b) overall consistent patterns emerge, although there are variations across regions and time; and (c) during the transformation process, both the order of importance and significance of the drivers change. Forest cover follows a consistent logistic decline pattern across regions, with introduced pastures being the major replacement land cover type. Forest stabilizes at 2–10% of the original cover, with an average patch size of 15.4 (± 9.2) ha. We discuss the implications of the observed patterns and rates of land cover change for conservation planning in countries with high rates of deforestation.

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1. Introduction

Human land use is the main factor responsible for ecological change on Earth from local to global scales. Transformation of natural ecosystems continues to increase globally, especially in the tropics and subtropics (FAO, 1997; World Resources Institute (WRI), 2001). A growing human population and a progressive global economy means that land use pressure will not slow down in the near future (Barbier and Burgess, 2001; Bilsborrow and Ogendo, 1992). The destruction of tropical forests is a major concern

because of the cumulative impacts on biodiversity, regional and global climate, and soil productivity (Geist and Lambin, 2001; Laurance, 1999). However, understanding and predicting the causes, processes and consequences of land use and land cover change is a major challenge to landscape ecology (Wu and Hobbs, 2002), and to regional land use planning and biodiversity conservation, which rely heavily on improved land use/land cover change data and models (Lambin and Geist, 2001; Lambin et al., 2001; Wu and Hobbs, 2002).

In Latin America, land clearing is recognised as a key ecological problem due to high, ongoing rates of deforestation (e.g. Bilsborrow and Ogendo, 1992; Laurance, 1999; Skole et al., 1994; Steininger et al., 2001). According to the latest estimates (Achard et al., 2002), the region's rate of tropical forest loss is 0.38% per year, creating concern especially because of the role Amazonian forests play in global climate. Correspondingly, the problem of

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deforestation in Central and South America has received most study and political attention. Colombia is one of the most biologically mega-diverse countries in the world, and hence highly sensitive to land cover change (Chaves and Arango, 1998; Myers, 1988). However, it is heavily impacted by human activities, with nearly half of the land area currently cleared of natural vegetation (Etter, 1998a).

In Colombia from the 1800s and up to the 1930s, land clearing rights were allocated on the basis of individual or collective rights, so that, in principle, at least the general location of land clearing could be predicted (Legrand, 1988). Since the 1950s, clearing has been mainly uncontrolled, creating a difficult planning scenario. During the past 50 years, lowland rainforests in Colombia have been substantially transformed due to population migrations, with a net loss of approximately 15% since 1970, but with wide regional variations (Etter, 1998b). Besides these general trends, little is known about land use change within Colombian ecosystems. Existing studies (e.g. Etter and Andrade, 1987; Garcia, 2002; Mendoza and Etter, 2002; Viña and Cavelier, 1998), are mostly descriptive with limited predictive capabilities, and would benefit from a more rigorous theoretical underpinning. Predictive models, empirically tested with real data, may help to describe the patterns and dynamics at regional and local scales. However, such models need to be grounded within existing land cover change theory.

Land cover change is a multi-scaled process, varying spatially and temporally with changing biophysical and socio-economic contexts (Wiens, 2002). Political and cultural factors play a key role in land cover change. In Colombia, most of the current land deforestation is taking place in national lands (forest reserves, national parks) in unplanned and often illegal colonisation fronts, which are out of control of the government. The patterns that this context creates are very different from the more planned schemes of Brazil and Ecuador (Dale et al., 1993; Sierra, 2000; Viña et al., 2004).

Further land cover change includes regrowth associated with abandoned pastures reverting to forest (Moran et al., 2000; Nagendra et al., 2003), often due to land abandonment. Some authors treat this as a one-way process (e.g. Mertens and Lambin, 1999; Pontius et al., 2001). Changing landscapes go through linked stability phases in the path of change, depending on the dynamics of the drivers causing them and the pattern-process relationships in the landscape itself. For example, tropical lowland rainforests undergo several stages of land cover change in colonisation fronts in Colombia. Clearing of forests often begins with small-scale subsistence agriculture, followed by planting of introduced pastures as a way of keeping land cleared. Recently subsistence crops have been replaced by illegal cash crops, but the pattern of small and isolated fields persists. In a later stage of the deforestation process, large areas are directly cleared for pasture and the establishment of semi-intensive cattle grazing. As infrastructure improves and accessibility to markets and land prices increase, grazing

areas may be partially replaced by intensive mechanised agriculture of perennials (e.g. oil palm, citrus) and annuals (e.g. rice, soybean). However, within the long-term pattern of deforestation, several mostly temporary transitions back to secondary forest occur scattered across the landscape.

Predicting the factors responsible for deforestation and forest regrowth is essential for advancing our understanding of the underlying patterns and drivers of land cover change (Moran et al., 2000; Nagendra et al., 2003; Soares-Filho et al., 2001). The paths of land cover change are often complex due to interaction of deforestation with the process of forest regrowth (Lambin, 1997). Often, the timeframes of change analysis are too short to effectively capture medium-term patterns of forest regeneration, and at best only explain short-term trends. The monitoring and reporting of land cover change at the national and regional scales is very important for raising the issue politically, but does not inform the spatial and temporal complexities of land cover dynamics occurring at the local scale. Mertens and Lambin (1999) and Lambin et al. (2001) point to the need for carefully grounded local context studies that address spatial and temporal complexities in order to avoid false conclusions from aggregated data. To enhance its contribution to sustainable land use and conservation planning, the study of land use and land cover change also needs to improve its explanatory and predictive capacity (Lambin et al., 2000; 2001). However, the political and economic forces that drive these factors are hard to predict, especially in view of the time lags between cause and effect.

This paper aims to contribute to land cover change theory, by developing and testing predictive models of deforestation and forest regrowth for selected Colombian ecosystems. First, we construct a general conceptual model of land use/land cover change at the local scale. Second, based on the literature, we formulate a set of testable a priori predictions of the effect of selected land use change drivers on the probability of transition from forest to non-forest and also from non-forest to forest. The a priori predictions are tested for a range of study areas located within Colombian lowland ecosystems. We then evaluate the predictive power of the different models and discuss their performance across regions and time-steps. Finally, some implications for the application of the approach in conservation planning are addressed.

2. Conceptual framework and a priori predictions

The existing theory on land cover and land use change recognizes several general principles derived mainly from landscape ecology and human geography. These principles focus on the effect of spatial and temporal scale on pattern and process, and the need for an interdisciplinary approach that encompasses the multi-thematic complexity of land cover change (Lambin and Geist, 2001; Liu, 2001; Liverman et al., 1998). Although many empirical models

fit land cover changes reasonably well, results of such studies are considered simplistic, because they are not spatially explicit, and are unable to explain and capture important land use processes (Geoghegan et al., 2001). Other authors have shown that simple models based on single or few variables can often predict deforestation with reasonable accuracy (Mertens and Lambin, 1997; Munroe et al., 2002). Complex models inherently have the drawback of high data requirements (multiple data sets, scale homogeneity, temporal replicates), which will in most cases not be available. Our inability to accurately and consistently model land cover change, remains one of the bottlenecks of the study of human-landscape interactions.

Understanding and predicting the underlying causes of land cover change is compounded by the complexity of these interactions due to: the multivariate nature of the biophysical and socio-economic factors that influence future changes (Liu, 2001; McDonnell and Pickett, 1993); the multi-scale properties of these interactions, whereby many of the driving factors operate at multiple spatial and temporal scales (O'Neill, 1999; Wiens, 2002); and, their either dynamic cyclical or directional nature, which collectively create intricate land cover change patterns (Forman, 1995).

The relative importance of different land cover change drivers may vary with the scale of analysis. Some factors are more relevant at broad scales (e.g. export markets, geopolitics, global economy), while others predominantly occur at finer or local scales (e.g. topography, soil fertility, land tenure, management practices) (Veldkamp and Lambin, 2001). What still needs to be explored in depth, is the timing and relative importance of the different drivers of change during the deforestation and forest regrowth processes. Specifically, the relative weight of drivers is expected to vary temporally as the transformation process advances and the landscape patterns change.

Based on the above theory, a set of premises about the patterns and processes of land use and land cover change are made:

- (i) land use drivers include multiple variables of human and biophysical origin that operate at different spatial scales;
- (ii) the action and significance of these variables may change in time; and
- (iii) land cover change typically includes multi-trajectory interacting processes, such as forest clearing and regrowth.

A general conceptual model derived from the available literature (e.g. Lambin and Geist, 2001; Mertens and Lambin, 1999; Moran et al., 2000; Read et al., 2001; Southworth and Tucker, 2001), showing the relationships between land use drivers and spatial and temporal patterns of land cover change is presented in Fig. 1. The conceptual model shows the land use drivers nested in four spatial scales (Fig. 1a): soil,

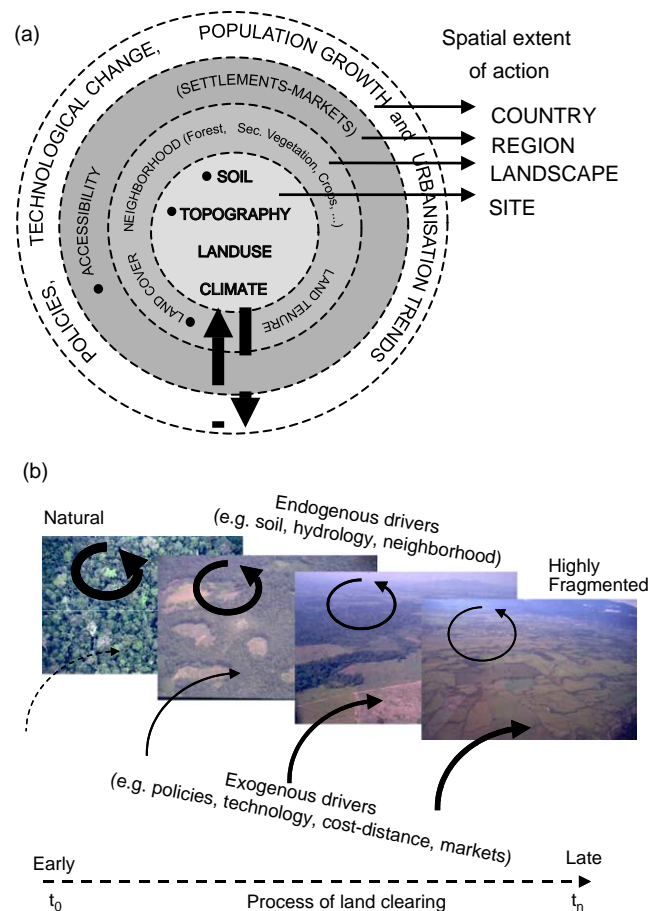


Fig. 1. Land cover change drivers in space and time: (a) spatial hierarchy of land cover change drivers, indicating their spatial range of action (marked with points are the factors addressed by this study); and (b) temporal trends in importance of the drivers during the land clearing process. The thickness of arrows indicates the predicted relative importance of the endogenous drivers (circular arrows inside the boxes) and the exogenous drivers (coming from outside).

topography, land use and climate at the site scale (10 s ha); land cover neighbourhood in the surrounding landscape (100–1000 s ha); accessibility to services and markets and land tenure at the regional scale (10,000s km²); and population growth, policies and technological change at the national scale (1,000,000 km²). Our study concentrates in four spatially explicit variables known to play a key role in the process of land cover change and for which we can get comparable quality data for different areas: soil fertility, land cover neighbourhood (forest and secondary vegetation), and a regional cost–distance function. We did not include climate and topography as those variables can be treated as constant within our study areas. Topographical variations are mostly of micro-topographical nature and not captured at the spatial resolution used here.

Because land use change is dynamic, we expect that the role and significance of the drivers will change temporally during the transformation process (Fig. 1b). The model predicts that variables operating at the local scale such as soil fertility will decline in importance as the transformation process advances

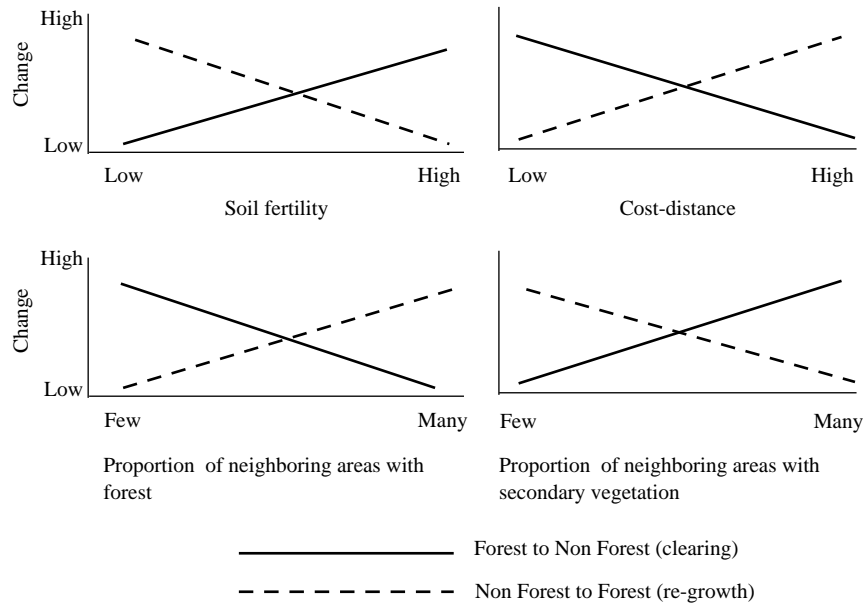


Fig. 2. General a priori predictions of the relationships between land use drivers and land cover change according to literature (e.g. Veldkamp et al., 1992; Mertens and Lambin, 1999; Lambin and Geist, 2001; Southworth and Tucker, 2001).

because of the improved accessibility, increasing scarcity of fertile soils, and the use of fertilizers and agricultural technology in the less fertile areas. In contrast, the exogenous regional and national drivers (e.g. cost–distance to markets) will increase in importance during the transformation process as the local economy becomes more interconnected with the regional and national economy and increased land prices enhance opportunities for credit access.

Embedded in the conceptual model are a set of a priori predictions for four spatially explicit variables at the site, landscape and regional scales based on the literature (Lambin et al., 2001; Mertens and Lambin, 1999; Southworth and Tucker, 2001; Veldkamp et al., 1992). Fig. 2 shows the predicted effect of soil fertility, accessibility to regional settlements, forest neighbours, and secondary vegetation neighbours on the magnitude and direction of change. For each location, two possible transitions in tropical forest cover are considered: forest clearing and forest regrowth. For each process, opposite effects of the variables on magnitude and direction are expected.

Five a priori models with an increasing number of variables are stated below, as a basis for testing the conceptual model and predictions in Fig. 2, for selected Colombian lowland ecosystems:

Soil (A priori model 1): Relative soil fertility is an important factor in the deforestation process (Veldkamp et al., 1992). With all other factors equal, we predict that the forests of more fertile soils tend to be cleared first. The opposite is true for forest regrowth, which is predicted to be higher on less fertile soils.

Cost–distance (A priori model 2): Access to infrastructure and markets strongly influences where the land clearing occurs (Ludeke et al., 1990; Read et al., 2001). We predict that more accessible forest areas have a higher chance of

being cleared, and that forest regrowth is more likely in more inaccessible areas.

Soil and cost–distance (A priori model 3): Soil fertility and accessibility are fundamental drivers and mutually reinforcing physical factors in forest clearing. We predict that a model incorporating them simultaneously will increase its predictive power.

Forest and secondary vegetation neighbourhood (A priori model 4): The type of land cover in the neighbourhood plays a significant role in the choice of forest clearing and land abandonment (e.g. Helmer, 2000). The importance and effect of these neighbourhood effects may vary over time depending on the land clearing process such as shifting cultivation or advancing colonisation fronts. Proximity to cleared land is predicted to be positively correlated with the probability of deforestation, while areas completely surrounded by forest are less likely to be cleared initially. The presence of secondary vegetation in the neighbourhood is predicted to decrease the chance of deforestation while increasing the probability of forest regrowth.

Combined model with all factors (A priori model 5): If all the selected parameters play a significant role, then a combined model of all parameters is expected to perform better in the explanation of the observed changes; and therefore will predict more accurately where and at what rates the future changes may occur.

3. Methods

3.1. Study area

Colombia (1.1 million km²) comprises five major regions: Andean, Caribbean, Pacific, Amazonian and

Orinoco, each with varied bio-geographical characteristics, due to the large altitude ranges (0–5800 m), climate variability (300–10,000 mm mean annual rainfall with plant growth periods ranging from 60 to 360 days/year), and the high diversity of geological substrates. By 1998, about 50% of the land area had been heavily transformed by human activities, with the Caribbean (>80%) and the Andean (65%) regions the most heavily transformed (Etter, 1998b; Etter and Van Wyngaarden, 2000).

Total human population in 2000 was approximately 40 million, with 75% living in urban areas, over half in the major cities. Historically, the majority of the population (65%) has been concentrated in the Andean region (Colmenares, 1999), before as well as after the arrival of the Spaniards. National average rural population density is approximately 30 inhabitants/km², but depending on the region can be lower than 5 (e.g. Amazon) or as high as 70 inhabitants/km² (e.g. Andean). Although the country has undergone strong ethnic mixing resulting in a dominant Mestizo population, cultural diversity is still high, with regionally contrasting rural cultures. The national economy is based on oil and coffee exports, although there is an increasing level of industrialization. Since the early 1900s, there has been a rural migration to lowland colonization fronts resulting in the loss of tropical forests. Nationally, the dominant land use is extensive cattle grazing. After 1990, Colombia opened its economy to the globalisation process causing substantial socio-economic impacts, especially on the agricultural sector. During the last 20 years, an economy of illegal export crops (coca and opium) has developed, especially in remote areas, creating social and political as well as environmental problems and concerns. Illegal crops have potentially important consequences for landscape transformation by redirecting colonisation patterns, and causing land abandonment in problem areas (Cavelier and Etter, 1995; Dávalos, 2001).

To test the five a priori models, six case studies of approximately 100 km² were selected from different lowland regions in Colombia, with an emphasis on tropical lowland forests (Fig. 3). Table 1 shows some general characteristics of the study areas and the temporal datasets available. Case study areas were selected on the basis of the following criteria:

- (i) largely transformed by human land use in 2000;
- (ii) availability of air-photos and satellite imagery as the empirical data source covering at least four dates over the period of transformation; and
- (iii) located in different bio-geographical regions.

3.2. Data sets

Data included standard black and white aerial photographs, multi-spectral satellite imagery (Landsat Enhanced Thematic Mapper), and supporting biophysical and

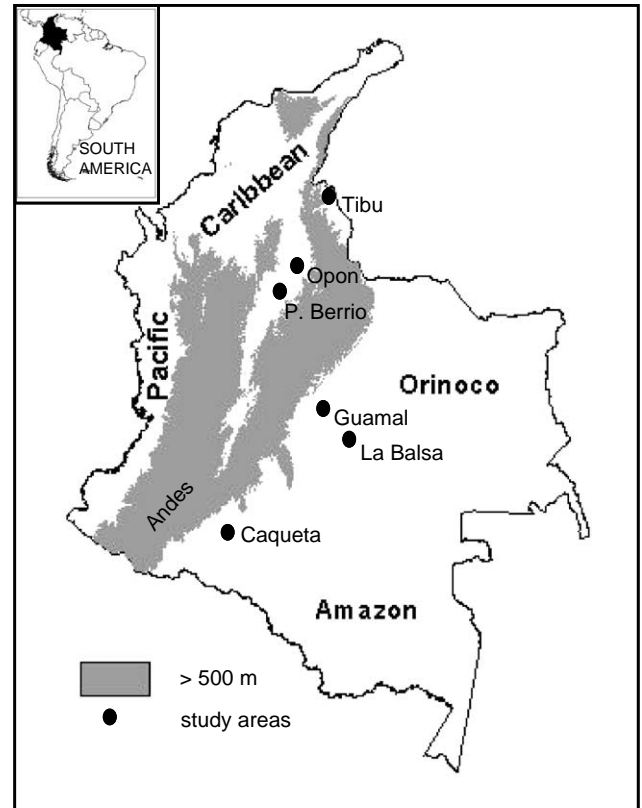


Fig. 3. Map of Colombia showing the location of case studies. Shaded area corresponds to the Andean region (> 500 m).

socio-economic data of comparable quality. Data extraction and analysis was conducted by visual interpretation, later digitised and converted to a uniform 1:50,000 scale for comparability. A general unified land cover classification composed of seven classes was applied to all areas (forest, secondary vegetation, savannas, introduced pastures, crops, water and urban), which were later aggregated to binary forest-non forest (1,0) maps in order to apply logistic regression.

Spatial data on all predictor variables were assembled from maps scaled to the 1:50,000 scale, and converted to raster maps with 100 × 100 m (1 ha) cell size. A soil map for each study area was constructed, using existing general soil maps of the Colombian National Geographic Institute (IGAC), and adjusted by means of physiographic photo-interpretation of the latest set of aerial photographs. Soil maps were classified and ordinally ranked on the basis of three broad fertility classes: low, moderate, and high. A cost–distance map was produced for each area and time-step as a measure of physical and economic accessibility. This was done using ArcView GIS vers.3.2, based on map layers of rivers, roads, terrain topography and surrounding settlements, and assigning differential friction values. Because roads change from date to date and are crucial to calculate accessibility, they were mapped from the aerial photographs for each date. Based on the raster land cover layers, maps of number of forest and secondary vegetation

Table 1
List of biophysical characteristics and data sets of study sites

Case study	Area (Km ²)	Region	Dates of air-photo coverage	Altitude (m)	Annual rain-fall (mm)/Nr. dry months	Original vegetation
La Balsa	128	Orinoco	1938, 1961, 1979, 1987, 1992, 2001	300	2500/4	Forest-Savanna mosaic
Guamal	140	Orinoco	1938, 1961, 1979, 1987, 1992, 1997, 2001	350	3000/3	Forest-Savanna mosaic
Caquetá	100	Amazon	1946, 1975, 1985, 1992, 2000	200	3400/2	Forest
Opón	68	Magdalena	1971, 1985, 1996, 2002	300	3200/1	Forest
Berrío	82	Magdalena	1950, 1961, 1977, 1985, 1996, 2002	120	3000/3	Forest
Tibú	74	Catatumbo	1961, 1975, 1985, 2000	150	2700/3	Forest

neighbours were produced in a 25 ha neighbourhood (5×5 moving window).

3.3. Patterns and rates of landscape change

To gain a general insight into the land cover change process of the different study areas, the following analysis were conducted: (a) calculation of the land cover transition probability matrices for land cover for each period was done using the map cross-tabulation function of Idrisi GIS Vers.3.2 (Clark-Labs, 2001); (b) curve fitting to temporal patterns of forest cover change; (c) calculation of annual rates of forest cover change for each time-step and study area; and (d) calculation of standard landscape metrics using the FRAGSTATS software (McGarigal and Ene, 2002).

The annual deforestation rates were calculated using the forest cover of the temporal series with the formula (Puyravaud, 2003):

$$\text{Rate} = \left(\frac{1}{t_2 - t_1} \right) \ln \left(\frac{A_2}{A_1} \right) \quad (1)$$

where A_1 is the forest cover at an initial time (t_1) and A_2 is the forest cover at the next time step (t_2).

3.4. Logistic regression

Forest clearing and regrowth were modelled and analysed using logistic regression in S-Plus (Insightful-Corporation, 2002), in order to explain the spatio-temporal patterns and some of the drivers of change. Logistic regression is a variation of ordinary regression when the dependent variable is of binary (0,1) nature, in this case change (1) and no change (0). In some cases the number of transitions is very low compared to the non-transitions, causing calculation problems. When the number of transitions (1–0 for deforestation, or 0–1 for forest regrowth) in a time-step made up a very small number compared to the non-changing cells, random samples of non-transitions were taken to adjust for their excess. The five a priori models were fitted to determine the transition probabilities of forest to non-forest (F–NF) and non-forest

to forest (NF–F) for each study area and time-step:

$$\text{logit}(y) = \beta_0 + \beta_1 X_1 + \dots + \beta_{k+1} X_{k+1} \quad (2)$$

The purpose of modelling was twofold: (i) assess the relative importance of the predictor variables for each a priori model; and (ii) select a best approximating model from the a priori set of candidate models. For each model the Akaike Information criterion (AIC) values were calculated, as a measure of their performance (Burnham and Anderson, 2002). Because the AIC is on a relative scale and dependent on sample size, the best approximating model was selected using AIC differences (Δ_i), as follows:

$$\text{AIC} = -2 \log \text{Likelihood} + 2K \quad (3)$$

where K , number of estimated parameters.

$$\Delta_i = \text{AIC}_i - \text{AIC}_{\min} \quad (4)$$

where AIC_i is the model's AIC value, and AIC_{\min} is the smallest AIC for all models of the time sets for each site.

The larger the Δ_i , the less plausible it is that the model best fits the data. Burnham and Anderson (2002, p. 70) present some rules of thumb that are particularly useful for nested models, where if,

$\Delta \in 0-2$ there is substantial level of empirical support

$\Delta \in 4-7$ considerably less support

$\Delta \in > 10$ essentially no support

The a priori predictions were evaluated by calculating the Akaike weight (w_i) for each of the candidate models using a practical information theory approach (Burnham and Anderson, 2002). The Akaike weight w_i can be used as an approximation of the probability that model i is the best model of R models (Appendix).

$$w_i = \frac{\exp(-\Delta_i/2)}{\sum_{r=1}^R \exp(-\Delta_r/2)} \quad (5)$$

To assess the importance of the predictor variables during the deforestation and forest regrowth processes, the statistically significant variables for each area, time-step and process ($N=32$) were ranked according to the t -values of

the result summaries of the combined model (Model 5). The relative frequency each variable ranked as most significant was then calculated.

4. Results

4.1. Landscape change patterns

Overall, the results show that across all areas during the last 60 years, the process of deforestation has resulted in a rapid decline of forest cover, and has typically been followed by extensive grazing, which tends to intensify where infrastructure development permits. A major aspect of the deforestation process is that, for all case study areas, forest loss is characterized by an asymmetrical logistic pattern, with four recognizable phases (Fig. 4):

- Phase i: initial phase with low rate of change;
- Phase ii: middle phase with highest rate of change;
- Phase iii: mid-late phase with rate of change slowing down; and
- Phase iv: final phase with an apparent new dynamic equilibrium of regrowth balancing forest loss.

When comparing the various regions, differences in colonisation waves and rates of deforestation are evident in the Amazon, Orinoco and Magdalena–Caribbean. The curve representing deforestation (Fig. 4), shifts in time depending on when the forest clearing process began. On average, the final stage (phase iv) is attained after 30–40 years, when the remnants of forest ecosystems reach between 2 and 10% of

their original cover. For all case studies, the dominant and more persistent replacement cover is introduced pastures, with crops representing a minor proportion of land use following deforestation.

The average annual deforestation rate across all areas and time-steps was 1.5% during the 1940–2000 period, reaching a maximum of 4.5% during phase (ii). In the case study areas, which are now predominantly cleared of their original forest cover, deforestation occurred mostly before the mid-1970s, especially from the 1960s. In phase (iv), a tendency of increased proportion of forest regrowth is recorded for all areas, except for Puerto Berrío. However, because the remnant forest area at this phase is low (approx. 5–10%), this recovery means little in terms of area, and could be partly explained by mapping error. Noteworthy, is that savanna ecosystems of the Orinoco region which occurred adjacent to rainforests (La Balsa, Guamal), show a relatively rapid transformation process, with annual clearing rates of up to 10%. In the same areas however, although in a more fragmented state, close to 80% of the original Gallery Forest corridors found within these Savannas have survived, and currently make up for most of the remaining forests in those areas.

The size of forest fragments shows an exponential decline during forest clearing in all study areas (Fig. 5), with the average size of the remnant forest patches in phase iv (> 90% deforested) a low 15.4 (± 9.2) ha. According to the model, when the cleared area reaches 50%, the average patch size is 200 ha, and falls below 100 ha with 60% forest clearing. When comparing the spatial pattern of the forest regrowth process, it is apparent that forest recovery does not always occur adjacent to existing forest, but can occur in

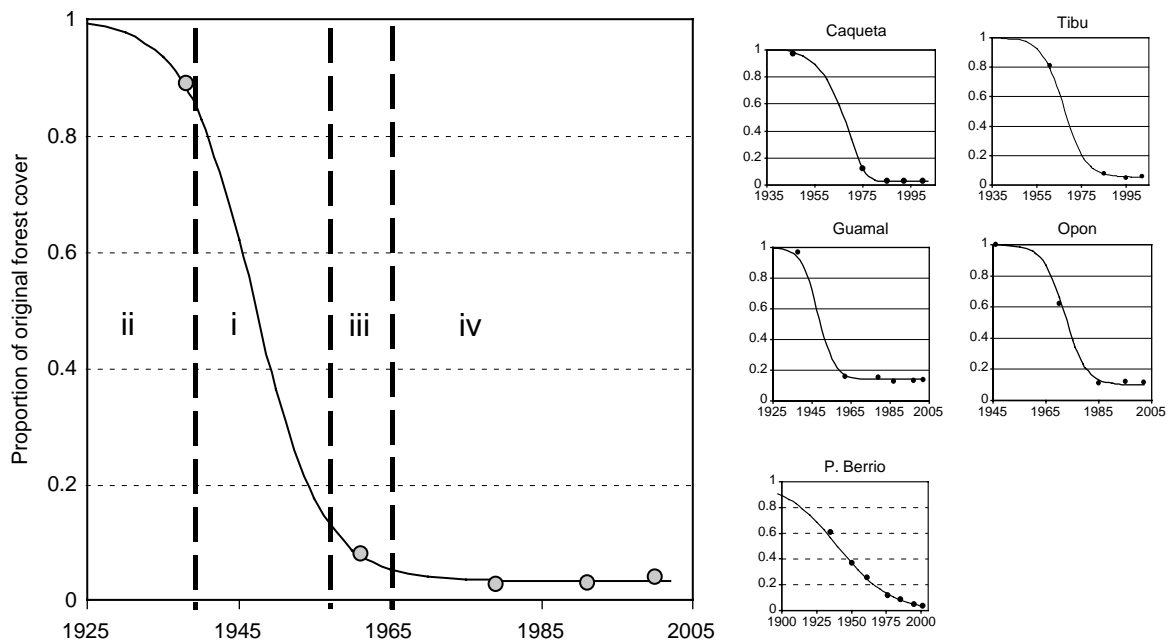


Fig. 4. Logistic pattern of the forest cover decline during the transformation process in Colombia, showing phases i–iv. Large plot corresponds to La Balsa case study, with equation: $Y = 0.033 + [0.967 / (1 + \exp(0.219 * (X - 1947)))]$.

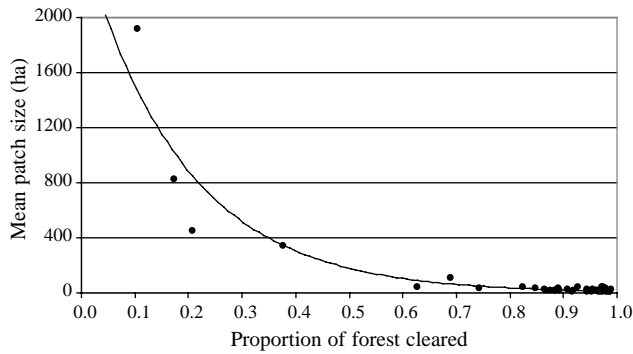


Fig. 5. Relationship between the proportion of cleared forests and mean patch size of forest fragments, across all study areas and time-steps.

different parts of the landscape. The average probabilities of forest regrowth shown by the change matrices for each time-step are low and in all cases do not exceed 0.1. In contrast, and as a consequence, the probability of a cleared forest cell remaining cleared is over 85%.

4.2. Model performance

Table 2 shows that the performance of the tested logistic regression models of forest transitions, differs between the processes of deforestation (F–NF) and regrowth (NF–F). In 46% of the cases the best performing model for deforestation was the combined model (Model 5), followed by Model 3 with 26%. However, for the process of forest regrowth, the better performing models were Model 4 in 48% of the cases, and Model 5 in 19% of cases. Overall, the factors that are most important in the deforestation process are the number of forest neighbours and soil fertility, while the number of secondary vegetation neighbours and cost–distance are more significant in the forest regrowth process (Fig. 6). However, the relative order of importance of factors changes from time-step to time-step, and varies from region to region, without any apparent pattern.

4.3. Testing predictions

The direction of the observed effect for soil fertility, cost–distance and number of forest neighbours are consistent with our predictions in Fig. 2, showing a distinct and

Table 2
Model performance comparing all areas and all time steps

Model	Deforestation F–NF (%)	Forest regrowth NF–F (%)
Model 1, SOIL	3	5
Model 2, CDIST	13	18
Model 3, SOIL + CDIST	26	10
Model 4, Forest neighbours + sec. vegetation neighbours	12	48
Model 5, All	46	19

The performance index is the percentage of areas/times for which each model had the best-weighted AIC value.

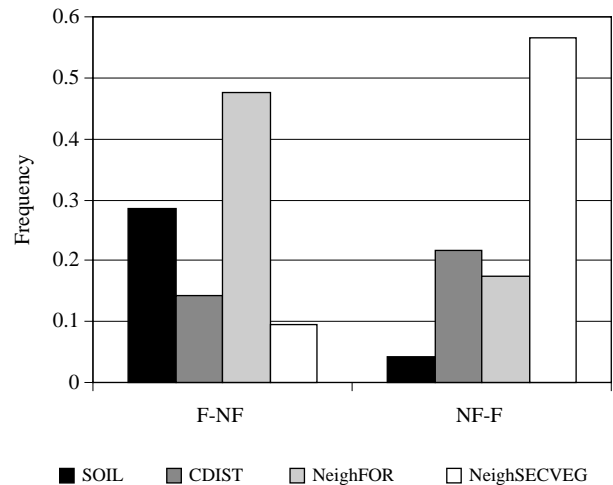


Fig. 6. Ranking of variables for deforestation and regrowth, according to the proportion of times a variable was the most significant in Model 5 across all areas and time-steps ($N=32$).

opposite effect for deforestation compared to forest regrowth (Table 3). However, the secondary vegetation neighbours effect is positive for both processes, and not in keeping with our predictions for deforestation.

The effect of drivers varies in magnitude across time-steps and from region to region, as seen through the logistic regression parameters plotted against the deforestation phases (Fig. 7). The average effect of the soil and cost–distance variables is, for the majority of cases, stronger but less constant, than that of the number of forest and secondary vegetation neighbour variables. Contrary to our predictions (Fig. 1b), the results show that soil fertility tends to increase in importance as deforestation proceeds. The opposite trend seems to be true for the re-growth process. In contrast, accessibility as measured through cost–distance shows an increasing although varied importance for regrowth over the four transformation phases, and a slight decline for deforestation.

5. Discussion

5.1. Models and model performance

Overall, the results largely confirm the predictions derived from general theory regarding the effect and relative

Table 3
General qualitative relationships between the tested variables and the deforestation (F–NF) and regrowth (NF–F) processes across all areas

Transition	Soil fertility	Cost–distance	Forest neighbours	Sec. vegetation neighbours
Deforestation (F–NF)	+	–	–	+
Forest regrowth (NF–F)	–	+	+	+

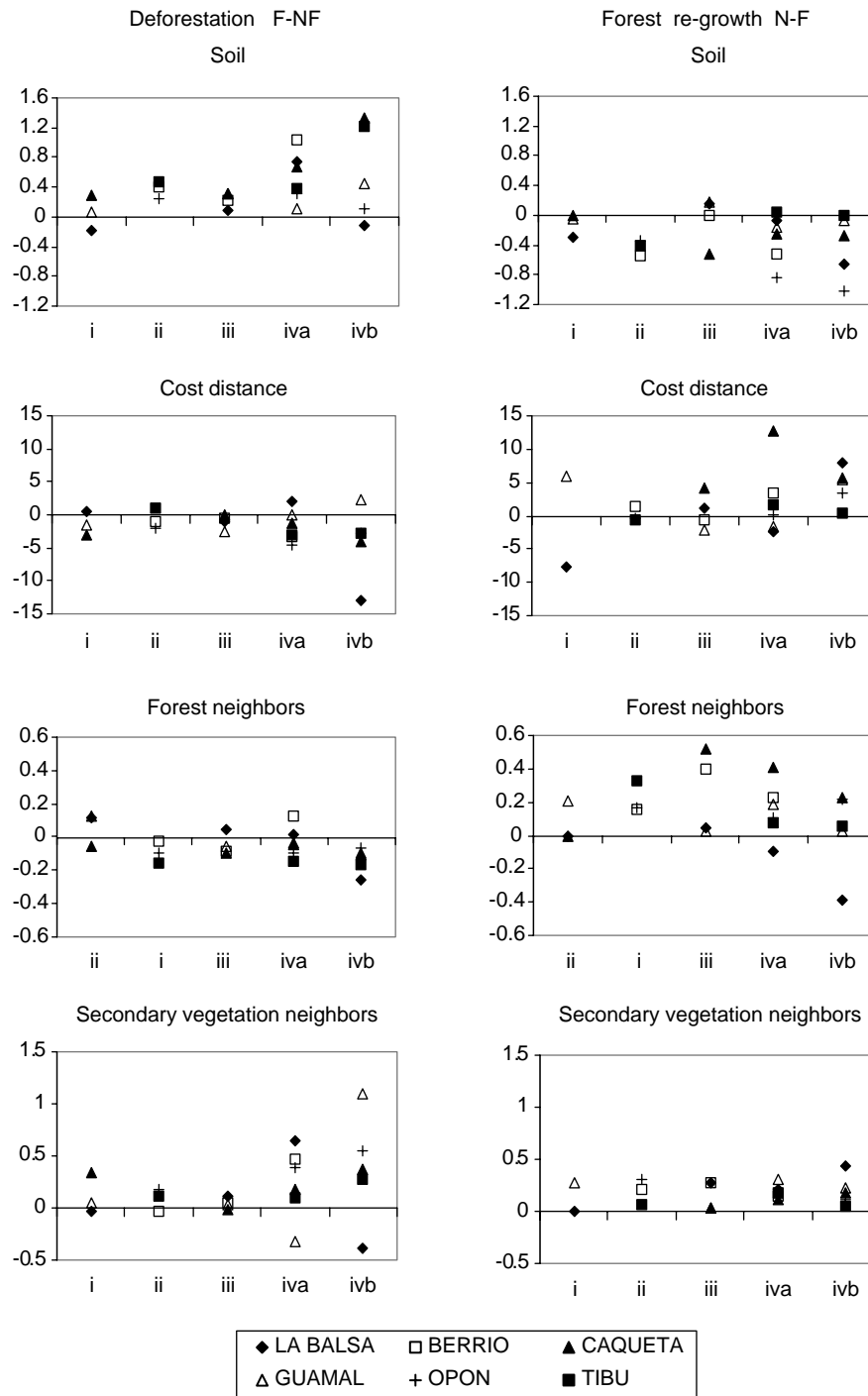


Fig. 7. Changes in the effect of explanatory variables across transformation phases for all case studies. Phase iv was split into iv_a (early) and iv_b (late). Points correspond to the non-standardized parameter values of the logistic regression.

importance of the different land cover change drivers. There are strong general trends in the relationships between variables (soil fertility, accessibility and forest neighbourhood) and the processes of deforestation and regrowth (Table 3). However, in some cases we found conflicting behaviour between time steps within one region, and also across regions. For example, the cost distance variable showed opposite trends for different time-steps in one

region, Caquetá, and has more erratic effects in regions where mosaics of savannas and forests occur (Balsa and Guamal). An unexpected result is that the influence of soil fertility tends to increase with the phase of transformation, which may be explained by a progressive increase in the farmers' ability to select high fertility soils as deforestation progresses, but is confounded by fertile soils becoming scarcer as deforestation proceeds. The influence of

accessibility, although being positively correlated with deforestation, tends to get weaker or negative in time. This can be explained by the colonisation front moving further away from settlements and infrastructure as the deforestation process advances.

Soil fertility has a clear positive effect on deforestation, supporting the results of Chomitz and Gray (1996); Veldkamp et al. (1992). However, the objective of forest clearing in many lowland areas is cattle grazing, which is less selective of fertile soils than agricultural cropping. Our results also confirm that roads tend to promote deforestation by increasing access to the forest frontier (Chomitz and Gray, 1996; Dale et al., 1993; Helmer, 2000; Nagendra et al., 2003). However, in Colombia roads are rare in the initial stages of colonisation. Mule tracks typically provide first access and are later improved by the national or state governments as settlements develop.

The number of secondary vegetation neighbours has mainly a positive effect on both deforestation and forest regrowth, and is therefore not helpful in discriminating between these processes. A possible explanation is that secondary vegetation is at the same time a necessary step of successful forest regrowth and also a consequence of deforestation.

5.2. Forest transitions and land use drivers

Deforestation is negatively related with the number of forest neighbours, especially after phase ii, meaning that deforestation occurs more along forest edges than deep within intact forest. In Colombia, the growth of secondary vegetation and forest recovery are scattered across the landscape, rather than close to forest edges as observed by Helmer (2000) in Costa Rica and Soares-Filho et al. (2001) in Brazil. Other factors such as management costs, armed conflict and land tenure are probably affecting the location and rates of forest recovery. However, although forest regrowth occurred to a certain extent in all study areas, it was balanced out by continued deforestation, as also shown by Read et al. (2001) in Costa Rica. This contrasts with the high regrowth levels reported by Nagendra et al. (2003) in Honduras. The patterns by which regrowth compensates for deforestation in phase iv, indicates that subtle changes in landscape dynamics will be overlooked if aggregate data are used, and can only be tackled if detailed spatially explicit models are used (Mertens et al., 2000; Munroe et al., 2002). In Colombia, forest regrowth is often an inverse function of agricultural suitability indicated by soil fertility and accessibility, a finding supported by Helmer (2000) in Costa Rica.

5.3. Temporal patterns

Deforestation consistently follows a distinct non-linear logistic pattern in all studied areas with distinct phases. Since the process of forest clearing is a function of the

labour invested in tree felling, and the amount of labour available is related to population size, the latter must have a positive impact on the process of deforestation. The population data of the 1993 census shows that the rural areas with the highest population growth are located in areas of active colonisation fronts such as Caquetá and Guaviare in the Amazon (DANE, 1993) where illegal crops are grown. However, the available demographic data lacks the spatial detail required for detailed local analysis such as applied here.

According to our results, the rates of deforestation vary greatly during the transformation process as a consequence of the negative logistic pattern. This makes it difficult to compare with rates observed by other studies where the reference phase of deforestation is not well known. Rates observed range from 1.2 to 4.5% forest loss per year, but can revert to a net increase in forest cover through regrowth in the later phases. Sierra (2000) found an average deforestation rate of 0.9% for the Ecuadorian Amazon, with rates up to 3.1% in localised subsets. For the tropical deciduous forests of the Bolivian lowlands, Steininger et al. (2001) estimates annual rates of up to 6% in peak periods. Comparisons with our results is risky, because we focused specifically on 100 km² case study areas, differing with the above in extent and context, and possibly also in the way land cover types are classified and mapped, in particular the forest types (Kleinn et al., 2002; Tucker and Townshend, 2000).

In areas that are now in the late transformation phase (ivb), the early deforestation phases occurred before 1970, when aerial photography was less frequent and more irregular, hence empirical data scarcer, which makes it difficult to establish the early rates of change (phase i and early ii) for transformed landscapes. After 1970 more frequent aerial photography is available, and, therefore, more accurate estimates of land cover change possible.

Our results show that remnant area stabilizes at between 2 and 10% of the original forest cover, with the explanation of spatial differences requiring further investigation of underlying factors such as topography, hydrology, soil conditions, land tenure and farm size. After 40 years of landscape transformation, the mean patch size of forest remnants is consistently reduced to 10–25 ha in all regions studied. Experimental studies on rainforest fragmentation in the Amazon (Laurance and Ferreira, 1997; Laurance et al., 1998), show that the vegetation composition and structure of fragments are heavily impacted by edge effects penetrating at least 100 m from the edge, with 100–400 ha fragment size being a critical threshold. Thus we expect in Colombia that the majority of forest remnants be subject to similar negative impacts associated with edge effects. However, the history described here would suggest that gallery forests of the savannas are less likely to be cleared than continuous rainforests. By contrast, the original savanna vegetation is being steadily eliminated from the landscape, a major concern for conservation.

5.4. Limitations and improvements

Although our models performed well as predictors of land cover change and confirm what other authors have found for Africa and Latin America (Mertens and Lambin, 1997; Munroe et al., 2002), several potentially important drivers (e.g. policies, land tenure, credit, demography) were left out of the analysis. It is not possible to evaluate how much improvement could be gained by introducing additional factors such as population size and the number of households, since spatially explicit data are not available for Colombia for the same spatial and temporal scales as used to quantify land cover change. Rural population density or perhaps more importantly the number of households in particular (Liu et al., 2003), may be well correlated with patterns and rates of deforestation (Rudel and Roper, 1997).

5.5. Implications for conservation planning

Conservation planning in highly dynamic landscapes experiencing rapid transformation has proven to be very difficult, especially where the transformation process is unregulated (Meir et al., 2004). In Colombia, colonisation fronts mostly occur on public lands, often designated as forest reserves. The conservation role of land cover change modelling in such a dynamic and rapidly changing scenario remains problematic and difficult to define. In theory, even when relying on clear objectives, planning should be highly adaptive. Steininger et al. (2001) documented the rapidity of clearance for the Bolivian lowlands when markets, government and international donors influence the process in a synergic way. Our study predicts that uncontrolled deforestation will reduce forest cover to between 2 and 10% of its original extent, which will have major implications for Colombia's rich biodiversity. Deforestation may only be controlled by adequate enforcement of illegal clearing, and by necessity in solving the underlying social and political problems. Because, as our study shows, deforestation occurs at a rapid rate, the timeframe for controlling and managing landscape transformation in the Colombian lowlands becomes very short. During the phase of rapid change, at the local scale, the original forest cover falls from 85% to less than 20% within 15 years, which means that the critical habitat retention and extinction thresholds for many species are surpassed in a very short time (Fahrig, 2001).

6. Conclusions

Deforestation across Colombian lowland moist forests shows a high degree of similarity in the temporal rates and spatial patterns, following a consistent logistic decline of forest cover. There is a similar overall effect of soil, spatial proximity to roads, rivers and towns, and forest and secondary vegetation neighbours, but their order of importance varies locally during the transformation process. Although the proportion of forests in the landscape at the final stage of transformation is very low (<10%), the counterbalancing processes of forest regrowth and deforestation contribute to a dynamic landscape structure, which needs to be considered in conservation management. There was little support for the hypothesis that patterns of influence of environmental variables such as soil, accessibility and neighbouring land cover, change consistently during the transformation process. However, we advocate that the dynamic influence of these variables be tested further, since incorporating such knowledge into the planning agenda has important potential implications for prioritising conservation actions. Finally, we emphasize that the rapidity of clearing of Colombia's lowland forests presents a major challenge to conservation planning. A research priority is a more detailed knowledge of the spatial and temporal impacts on ecosystems and the biota in this high diversity region, before it is too late.

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Appendix

Example of the modelling results for the Puerto Berrío area, showing the relative AIC weights of each model and time step.

Forest to non-Forest

Period	Parameters	log Lik	AIC	Δ_i	w_i
1950–1961	SOIL	–2401.401	4804.80	21.178	0.00002
	CDIST	–2401.681	4805.36	21.740	0.00001
	SOIL + CDIST	–2401.243	4806.48	22.864	0.00001
	NeighFOR + NeighSVEG	–2389.811	4783.62	0.000	0.78037
	SOIL + CDIST + NeighFOR + NeighSVEG	–2389.079	4786.15	2.536	0.21959

(continued on next page)

Period	Parameters	log Lik	AIC	Δ_i	w_i
1961–1979	SOIL	–1526.541	3055.08	15.128	0.00046
	CDIST	–1527.941	3057.88	17.930	0.00011
	SOIL + CDIST	–1520.002	3044.00	4.052	0.11643
	NeighFOR + NeighSVEG	–1532.082	3068.16	28.212	0.00000
	SOIL + CDIST + NeighFOR + NeighSVEG	–1515.976	3039.95	0.000	0.88299
1979–1985	SOIL	–1519.761	3041.52	36.676	0.00000
	CDIST	–1521.113	3044.22	39.380	0.00000
	SOIL + CDIST	–1519.739	3043.47	38.632	0.00000
	NeighFOR + NeighSVEG	–1502.512	3009.02	4.178	0.11017
	SOIL + CDIST + NeighFOR + NeighSVEG	–1498.423	3004.84	0.000	0.88983
1985–1995	SOIL	–1109.243	2220.48	16.494	0.00026
	CDIST	–1121.619	2245.23	41.246	0.00000
	SOIL + CDIST	–1107.525	2219.05	15.058	0.00054
	NeighFOR + NeighSVEG	–1115.357	2234.71	30.722	0.00000
	SOIL + CDIST + NeighFOR + NeighSVEG	–1097.996	2203.99	0.000	0.99920
1995–2001	SOIL	–691.663	1385.32	25.333	0.00000
	CDIST	–694.176	1390.35	30.359	0.00000
	SOIL + CDIST	–689.017	1382.03	22.041	0.00001
	NeighFOR + NeighSVEG	–678.986	1361.97	1.979	0.27097
	SOIL + CDIST + NeighFOR + NeighSVEG	–675.997	1359.99	0.000	0.72902
Non-Forest to Forest					
1950–1961	SOIL	–784.397	1570.79	39.656	0.00000
	CDIST	–782.506	1567.01	35.873	0.00000
	SOIL + CDIST	–781.880	1567.76	36.622	0.00000
	NeighFOR + NeighSVEG	–763.569	1531.13	0.000	0.99995
	SOIL + CDIST + NeighFOR + NeighSVEG	–771.495	1550.99	19.850	0.00005
1961–1979	SOIL	–1454.741	2911.49	17.184	0.00019
	CDIST	–1455.073	2912.15	17.846	0.00013
	SOIL + CDIST	–1454.392	2912.79	18.486	0.00010
	NeighFOR + NeighSVEG	–1445.156	2894.31	0.000	0.99958
	SOIL + CDIST + NeighFOR + NeighSVEG	–1456.946	2921.89	27.580	0.00000
1979–1987	SOIL	–670.306	1342.61	20.468	0.00003
	CDIST	–669.123	1340.24	18.103	0.00011
	SOIL + CDIST	–668.506	1341.01	18.868	0.00007
	NeighFOR + NeighSVEG	–659.072	1322.14	0.000	0.91984
	SOIL + CDIST + NeighFOR + NeighSVEG	–659.514	1327.02	4.885	0.07994
1985–1995	SOIL	–293.740	589.48	4.244	0.05862
	CDIST	–291.698	585.39	0.159	0.45194
	SOIL + CDIST	–290.618	585.23	0.000	0.48944
	NeighFOR + NeighSVEG	–314.118	632.23	47.000	0.00000
	SOIL + CDIST + NeighFOR + NeighSVEG	–332.623	673.24	88.009	0.00000
1995–2000	SOIL	–292.645	587.29	18.205	0.00011
	CDIST	–291.558	585.11	16.031	0.00031
	SOIL + CDIST	–291.177	586.35	17.270	0.00017

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