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# Physical and social access to land: spatio-temporal patterns of agricultural expansion in Madagascar

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## Abstract

The expansion of agriculture is posited as one of the main dynamics of land cover change globally, and the robust modeling of these processes is important for policy as well as academic concerns. Madagascar's farmers stand accused as the "proximate agents" of land conversion in one of the world's "hottest" biodiversity hotspots, and numerous studies have been conducted to describe and model the processes by which the country's forests are giving way to agriculture. This paper concerns a relatively small area on the island's eastern escarpment where considerable national and international attention has been paid to slow the expansion of agriculture into the remaining natural forests. The approach adopted here is to begin by examining the degree to which patterns of agricultural conversion can be attributed to a set of factors that have been identified as significant at broader scales in Madagascar and elsewhere, namely topography and prior human settlement and land use patterns. A regression model is constructed, and its predictions compared to the observed land conversion over a 43-year period. The study then examines in detail the spatial patterns highlighted by the failure of the model (the residuals of the regression), breaking the study area into smaller zones, or landscapes. The spatio-temporal trajectories of these zones are then contrasted, with particular attention to the institutional arrangements governing access to land resources. The study finds that while overall land change patterns in the region are largely explained by elevation and village proximity, more specific, sub-regional, trajectories reflect the signatures of institutions governing access to land.
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## 1. Introduction

The science of land change analysis is advancing rapidly, with the development of increasingly sophisticated, reliable and accessible tools and techniques (McConnell, 2001). Perhaps the most effort has been devoted to the modeling of deforestation processes including, inter alia, agricultural expansion (see reviews by Lambin (1994), Kaimowitz and Angelsen

(1996), Geist and Lambin (2002), Veldkamp and Lambin (2001)). In addition, a large body of literature is developing on the use of landscape pattern metrics to understand the qualities of a given landscape, both in terms of ecological functions and services, and in the detection of human influence in shaping that environment (e.g., Batistela et al., 2000; Forman, 1995; Southworth et al., 2002). These two fields of endeavor come together in the study of the trajectories, or pathways, of land change (Brondizio et al., 2002; Mertens and Lambin, 2000; Turner et al., 1995).

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robust modeling of these processes is important for policy as well as academic concerns (Lambin et al., 1999, 2001). Madagascar's farmers stand accused as the "proximate agents" of land conversion in one of the world's "hottest" biodiversity hotspots (Myers et al., 2000), and numerous studies have been conducted to describe and model the processes by which the country's forests are giving way to agriculture (Gade, 1996; Jolly, 1987; Keck et al., 1994; Laney, 2002; Olson, 1984). This paper concerns a relatively small area on the island's eastern escarpment where considerable national and international attention has been paid to slow the expansion of agriculture into the remaining natural forests (Kramer et al., 1997; McConnell, 2002; Messerli, 2000; Schoonmaker-Freudenberger, 1995) (Fig. 1).

The expansion of agriculture—at the expense of forest cover—in the region from 1957 to 2000 is illustrated in Fig. 2. Even a cursory examination of these maps reveals that this expansion has been discontinuous in both time and space, and the objective of the research presented here is to characterize these discontinuities. We suspect that these spatio-temporal patterns are related to differential institutional arrangements governing access to land resources, specifically the formal and informal rules regulating forest fallow agriculture and other forms of resource exploitation. The approach adopted here is to begin by examining the degree to which the patterns of agricultural conversion can be attributed to a set of factors that have been identified as significant at broader scales in Madagascar and elsewhere, namely topography and prior human settlement and land use patterns (Green and Sussman, 1990; Rao and Pant, 2001). A regression model is constructed, and its predictions compared to the observed land conversion over a 43-year period. The study then examines in detail the spatial patterns highlighted by the failure of the model (the residuals of the regression), breaking the study area into smaller zones, or landscapes. The
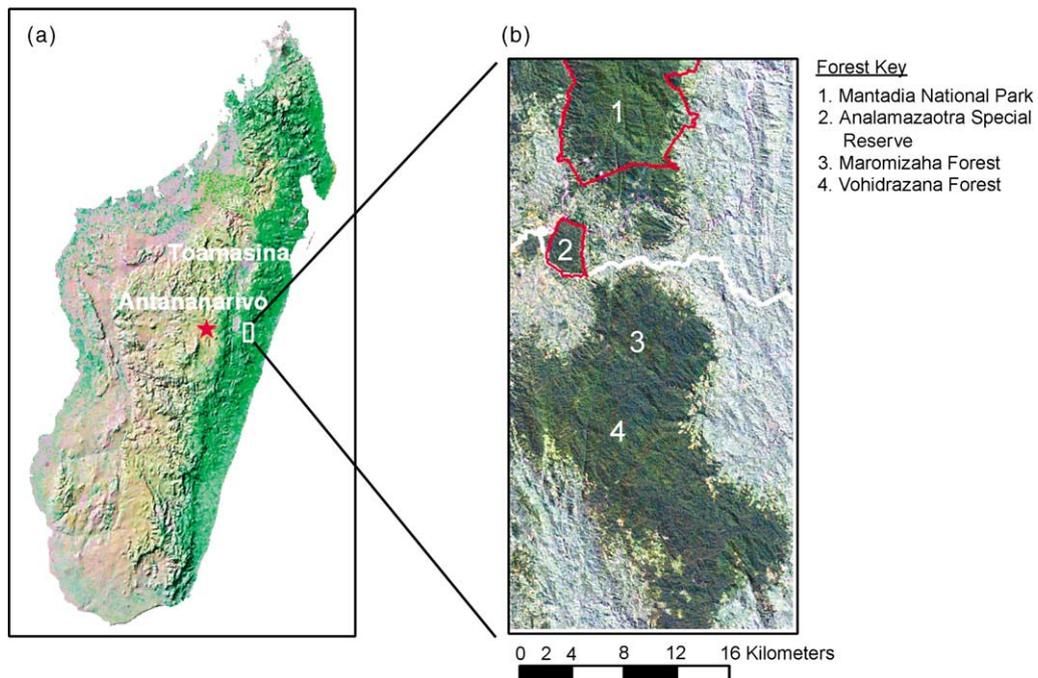


Fig. 1. Location of the study area: Madagascar lies some 400 km off the coast of Mozambique, in the Indian Ocean. The study area is in the mountainous eastern escarpment, within a half-day's drive of the capital, Antananarivo. The study area comprises approximately 940 km², bounded by the following coordinates (in Laborde meters, Madagascar's unique map projection)—X: 605,544–627,174; Y: 765,996–809,376. (a) Map of Madagascar with vegetation overlay courtesy of ANGAP; (b) the study area as seen by the Landsat ETM+ sensor (see Fig. 2). Forests appear in dark green. The RN2 highway horizontally bifurcates the region.

(a) 1957          (b) 1976          (c) 1994          (d) 2000



**Land Cover**

◼ Forest

☐ Agriculture
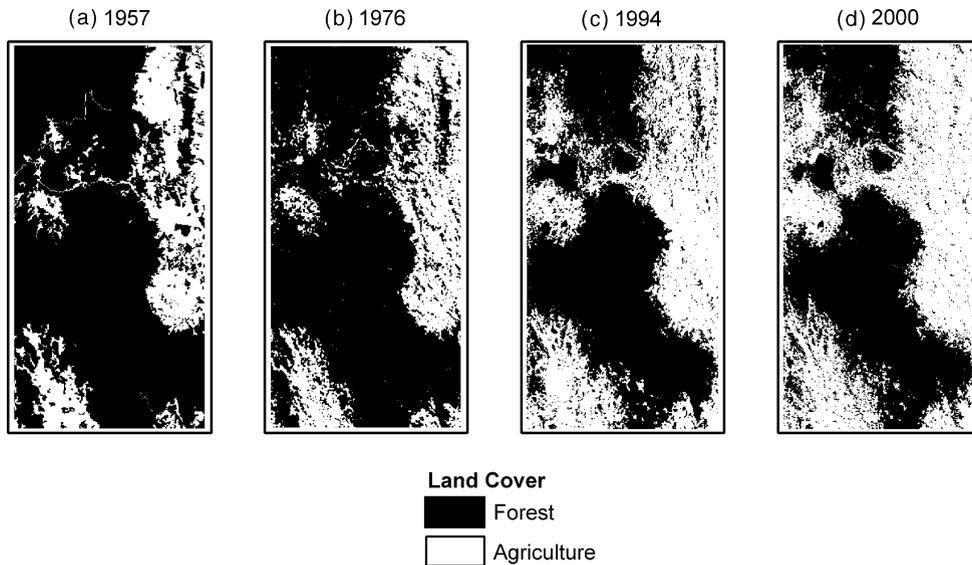
Fig. 2. Land cover in the study area. Sources: (a) IGN/FTM topographic maps S-47N and S-47S (PERINET and LAKATO), based on aerial photographs from 1957, scale: 1:50,000, projection: Conformal Laborde, publisher: L'Institut Geographique National (France)/Foiben-Taosarintanin'I Madagasikara (Madagascar); (b) Landsat MSS, 5 June 1976, Scene ID: LM2169073007615790; (c) Landsat TM, 21 November 1994, Scene ID: LT5158073009432510; (d) Landsat ETM+, 19 April 2000, Scene ID: LE7158073000011050.

spatio-temporal trajectories of these zones are then contrasted, with particular attention to the institutional arrangements governing access to land resources.

## 2. Methodology

### 2.1. The study area

The study area is found in Madagascar's eastern escarpment between the Indian Ocean and the island's central highlands (see Fig. 1). The local topography is quite rough, ranging from summits well over 1300 m a.s.l., to just over 200 m a.s.l. along rivers draining these mountains eastward to the ocean. The mountains intercept moist air moving inland throughout the year, resulting in annual precipitation in excess of 1800 mm, and cloud forest formations at the higher elevations. A corridor of intact rainforest running approximately 150 km north-south along this part of the escarpment has attracted intense national and international attention centered on conserving the habitat of the *Indri indri* lemur, and other endemic—and endangered—flora and fauna of the region.

The earliest evidence of human presence on the island has been dated at less than 2000 years ago, and local residents of the study area estimate that their villages may have been founded in the early 20th century. Traditional land use in the region is characterized by itinerant rainfed hillrice cultivation, known in the Malagasy language as *tavy* (and in other parts of the world under the pejorative term "slash-and-burn" agriculture). This involves the felling of trees, which are then left to dry before being burned to clear the brush and release nutrients to the soil, prior to the planting of rice grains with the aid of a dibble stick. Fields are typically cultivated for one, or at most two, successive seasons, and the land is then allowed to lie in fallow before being cultivated once again. During the *tavy* season, families live in temporary shelters near their fields, while maintaining permanent dwellings and granaries in the village center, typically located along major water courses.

Physical and social constraints on the clearing of new agricultural land in the region mean that fields are generally cleared again during their *savoka* phase (3–10-year fallow), rarely attaining secondary forest (*jingeranto*). Physical limitations include the

steepness of the land, as some slopes are simply too severe to permit sowing and harvesting. Proximity to the permanent village site, however, does influence preferences, as transport of the crop to the granary is quite difficult in the steep terrain. Social factors affecting *tavy* are discussed below. While *tavy* is the core of the agricultural system, a number of other crops—both for consumption and for sale—are cultivated, usually in close proximity to the permanent village site. A great deal of conservation and development effort has been devoted to convincing farmers to diminish or abandon *tavy* cultivation in favor of permanent agriculture, in hopes that this will limit the conversion of forest habitat for new fields (Messerli, 2000; Razakamarina et al., 1996; see also Terre Tany/ BEMA: http://www.cde.unibe.ch/programmes/africa/ afr25.html).

Access to farm land is traditionally governed under a system built around lineage relations with the initial founders of the village, and are under the tutelage of a community land chief (*tangalemena*) and his council (*ray aman dreny*). Special restrictions govern the use of sacred land around family tombs (*sembontrano*) and taboo (*fady*) forest stands (Schoonmaker-Freudenberger, 1995; McConnell, 2002). Since the first edicts of the Merina monarchs in the early 19th century, all the island's forests have been under formal state control, and the remaining forests of this region are now managed under various forms of state protection (Kull, 1996). These include the 10,000 ha Mantadia National Park and the 810 ha Analamazaotra Special Reserve, the core areas of the Andasibe-Mantadia Protected Area (APAM) complex, lying along the highway and railroad that connect the country's main port, at Taomasina, with the highland capital, Antananarivo. Surrounding—and sometimes contiguous with—these forests are several others that are managed either as protected area "buffer" forests (e.g., Maromizaha), or as less restrictive *forêt classée* (e.g., Vohidrazana). Industrial logging concessions are actively being worked in some forests of the region (esp. in the north), and some smaller scale, and occasionally illicit, logging takes place elsewhere. In addition, graphite mining is a significant land use to the east of the Mantadia Park. Tourism in the Special Reserve, and more recently in the National Park and its Buffer Zone, is a growing source of revenue in the area (Razakamarina et al., 1996; McConnell, 2002).

The study area was delimited to encompass the range of forest protection described above. It comprises about 940 km$^2$ covered by the two 1:50,000 scale topographic maps, S-47n "Perinet" and S-47s "Lakato."

### 2.2. Data preparation

Several field visits were made to the study region from 1994 to 2000, and entailed collective and individual interviews with farmers and conservation staff, as well as forest mensuration and "training sample" data collection, as described below.

#### 2.2.1. Land change

In this study, the "dependent variable" is land converted from forest to agricultural use over a period of 43 years (1957–2000), derived from several sources. The baseline data were captured from the 1:50,000 scale topographic maps mentioned above, which are based on vertical panchromatic aerial photography of approximately the same scale, flown in 1957. The maps were scanned at 300 dpi, yielding a nominal ground resolution of 4.25 m. The R2V$^®$ vectorization software was used to capture two land cover classes, agriculture and forest. The examination of two stereo pairs of the original analogue photographs in a stereo Zoom Transferscope$^®$ led to a high degree of confidence in the representation of these two classes on the source maps. The remaining land cover maps were derived from supervised classification of Landsat MSS (1976), TM (1994) and ETM+ (2000) images, georectified to the topographic maps in a master-slave process to achieve a "fit" (total RMS) among the images of better than 15 m.

The supervised classification was effected using "training sample" data collected according to protocols developed by the Center for the Study of Institutions, Population and Environmental Change (CIPEC, 1998). The most recent imagery used was acquired by Landsat 7 in early 2000, the year before the main field visit. The training samples for agricultural plots therefore included information on plot histories to aid in the delineation of different aged fallows, and in the classification of previous satellite images. The training samples were supplemented by GPS-referenced panoramic terrestrial photographs, as well as near-vertical panchromatic aerial photographs

acquired in 1991 and low-altitude color aerial photographs acquired in 1996.

### 2.2.2. Topography

The first set of "independent variables," or explanatory factors, are topographic, including elevation and its first derivative, slope. Three input vector coverages were captured from the same 1:50,000 topographic map series mentioned above, including 50 m-interval contours, point elevations, and streams. A digital elevation model (DEM) was then constructed from these vector coverages with the ANUDEM program implemented in the TOPOGRID function in ArcInfo® (ESRI, 1983–2001). The algorithm employed by ANUDEM interpolated elevation data onto a grid while enforcing drainage constraints (stream and elevation points), eliminating errors such as pits and sinks, and ensuring an accurate representation of ridges and streams. The output was a continuous grid of floating point elevation values (Fig. 3a).

The SLOPE command, available as a GRID function in ArcInfo®, was used to produce a continuous surface of floating point values (Fig. 3b) utilizing the Average Maximum Technique (Burrough, 1986: 50) which calculated the slope value of each cell from a 3 by 3 neighborhood. The resulting slope model exhibits artifacts known as "shadow contours" that often occur when slopes are calculated from DEMs derived from the interpolation of contours, acknowledged in the software help file as follows: "There is a slight biasing in the interpolation algorithm that causes input contours to have a stronger effect on the output surface at the contour. This bias can result in a slight 'flattening' of the output surface as it crosses the contour" (ESRI, 1983–2001). To evaluate the possible effects of the shadow contour artifacts on the study results, the original contours were rasterized and combined with the land cover change grid. The number of pixels possessing contour values was calculated for each change class. The two key change classes analyzed, (forest → forest) and (forest → agriculture), were found to contain very similar proportions of contours, 25.07 and 24.88%, respectively, indicating that any effect of the flattening is shared equally across those classes.

### 2.2.3. Demography

The next set of explanatory factors relate to prior settlement and land use. The most commonly used

spatial demographic data in Madagascar, as elsewhere, are those generated by national population censuses. Two sets of census boundaries have been developed in Madagascar, for the censuses of 1966 and 1990. Neither of these sets of boundaries could be used for the present study. The *Atlas de Madagascar* (Association des Géographes de Madagascar, 1969) mapped population density at the *canton* level, typically larger than the entire area treated here. Boundaries for the 1990 census data are available at the *firaisanampokontany* level (the new version of *commune rurale*, a subdivision of the prior *canton*), but the present study area still consists of portions of five *firaisana*, so these data were of no more use than the 1966 boundaries. Village boundaries are not depicted on the topographic maps, as their delineation is a tricky technical, and even political, undertaking. In daily practice, village boundaries are flexible, porous constructs. It is not uncommon for a resident of a neighboring community to obtain temporary use of land through a simple request, and inter-village marriage and inheritance can render the notion of a village boundary meaningless or, perhaps worse, misleading.

By and large, however, farmers mainly seek farm land from their own *tangalamena*, and demand for forest land in a given locale can be expected to vary as a function of community land pressure (i.e., persons per $km^2$). In the absence of cartographic boundaries, population density can be estimated from the distribution of residential structures, which appear on the topographic maps, based on the 1957 aerial photographs. Inspection of the stereo pairs revealed that the original photo-interpretation involved a very systematic simplification of the photographs, assigning a *construction* symbol to each set of 5–7 structures visible in the photographs. Village centroids were therefore captured from the digital versions of the maps, visually located at the centers of named building clusters (village), and the number of structures shown attributed to each centroid. Outlying symbols carrying no name, presumably hamlets, were assigned to the nearest village center.

Several demographic surfaces were constructed from the village centroid data. Comparative analysis of different approaches for the approximation of functional village territories has differentiated "discrete" and "fuzzy" methods (Crawford, 2002; Walsh et al., 2001). The first surface generated here applied the logic of tessellation, which subdivides the region into

(a)

(b)

(c)

260 ■■■□□ 1307
Meters

0 ■■■□□ 59
Degrees

⊙　Village Centroids

(d)

(e)

(f)

0 ■■■□□ 8224
Meters

26 ■■■□□ 88
Population "Pressure"

0 ■■■□□ 8846
Meters
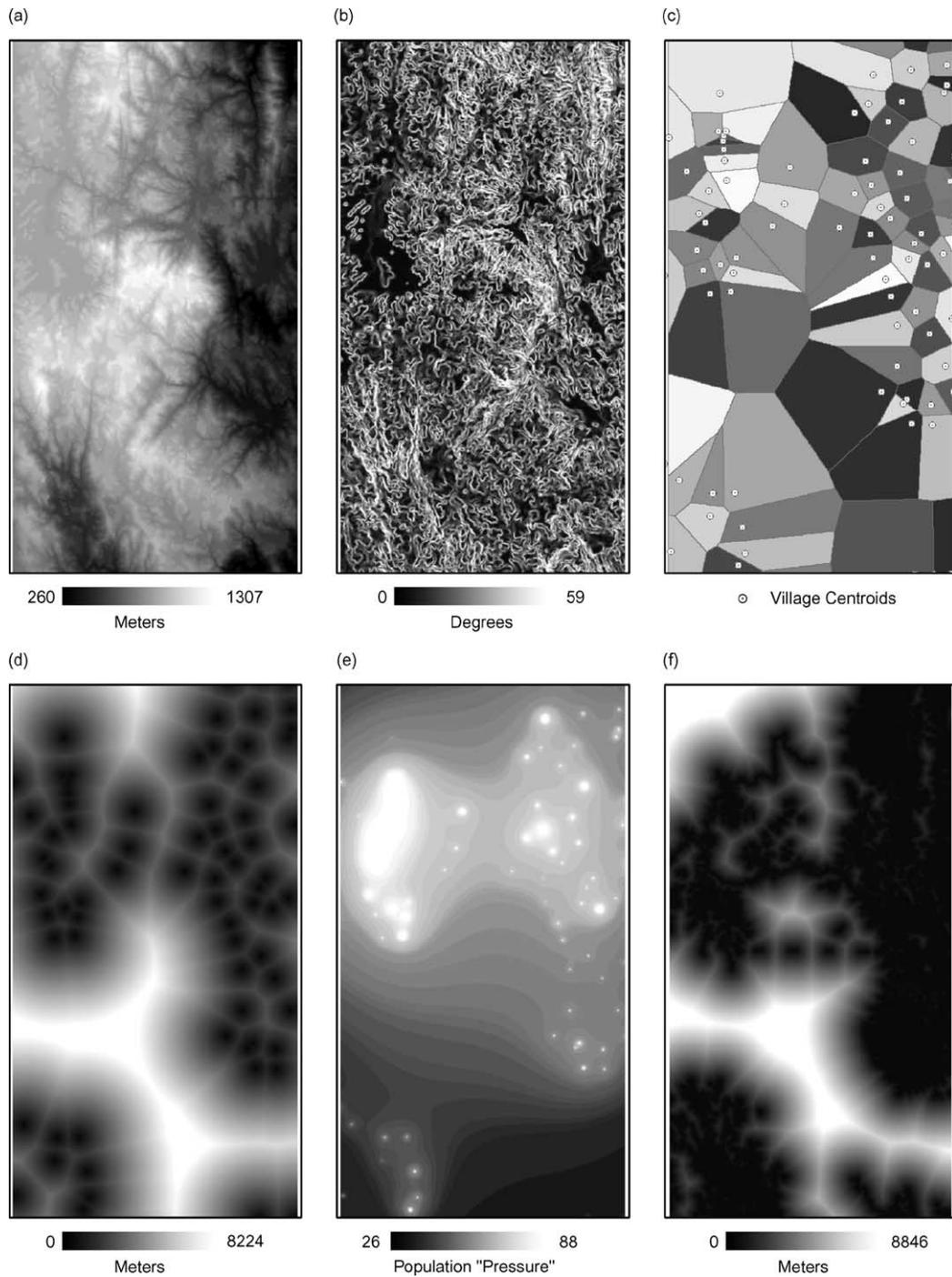
Fig. 3. Explanatory factors: (a) DEM in meters above sea level derived from contours digitized from 1:50,000 scale topographic maps (see Fig. 2); (b) slope model, in degrees, derived from the DEM in Fig. 3a; (c) Thiessen polygons, showing the theoretical zones of influence of the village clusters (centroids); (d) distance from villages (centroids) in meters; (e) potential population model calculated from village clusters (centroids) using a distance weight exponent of 2, and no search radius limitation; (f) distance from the (1957) forest edge, in meters.

discrete village territories by constructing boundaries at the midway point between each village and its neighbors. The boundaries resulting from the tessellation are quite rectilinear, but follow a straightforward logic and are perhaps the best approximation to be made. The village polygons were assigned the number of structures mapped and these were used in conjunction with the areal extent of each polygon to derive a choropleth model of relative population density (see Fig. 3c).

The next set of demographic surfaces was generated by a different, fuzzy, logic: rather than subdividing the region, the influence of each population centroid was "spread" through the study area. The simplest logic for this is to simply calculate the distance of each raster cell from an undifferentiated set of points. The DISTANCE module in Idrisi32® (Eastman, 2001) was used for this purpose, resulting in a continuous surface of values increasing radially from each centroid, with pixel values representing the distance in meters from the nearest village centroid (see Fig. 3d). The inverse of this surface is one expression of population "pressure."

To take account of the number of people (structures) present at each centroid, as well as the neighborhood influence of surrounding villages (centroids), a set of more complex surfaces was generated through interpolation. Idrisi32's INTERPOL module was used to create a set of gravity—or potential interaction—models, using distance decay exponents of 0.5, 0.75, 1.0 and 2.0. The procedure produces continuous surfaces of theoretical population density with peaks at the village centroids determined by the initial value at that point, influenced by the initial values of other points according to their respective distances (see Fig. 3e). The higher the decay rate, the more rapidly the surfaces tend towards zero in uninhabited areas. A distance weight exponent of two yields a weight equal to the reciprocal of the distance squared. Given the sparse distribution of points in this case, decay rates greater than 2.0 produced very high peaks at centroids, with almost no "spread," while exponents lower than 0.5 "spread" the population unrealistically evenly across the landscape (see Walsh et al., 2001). Likewise, with small number of input points, it is recommended that no search radius limitation be imposed (Eastman, 2001), therefore all points were included in the interpolations.

### 2.2.4. Spatial inertia

Finally, another factor was generated to model the likelihood that agricultural expansion would follow directly on from prior expansion—what has been called the "spatial inertia" effect (Mertens and Lambin, 2000: 491). This was accomplished by calculating the distance of each forest cell at the outset (1957) from the nearest agricultural cell (see Fig. 3f).

### 2.3. Analytical methods

The analysis of agricultural expansion was carried out in three stages, the first two designed to assess the relationships of several spatially explicit biophysical and social factors with land change throughout the study region as a whole. This led to the identification of anomalies—areas where agricultural conversion did not follow the pattern evident in the study area as a whole. The third step, then, was to segment the study area into constituent landscapes to enable a closer examination of the processes operating in each, with particular attention to the spatial configurations (i.e., the fragmentation of forest) through several time periods.

### 2.3.1. Change detection

The simplest way to assess the effect of the explanatory factors is to compare their characteristics in those areas where forest was converted to agriculture vis a vis those areas where forest remained intact over the entire 43-year period. Change detection was accomplished by cross-tabulation of the 1957 and 2000 land cover maps, yielding four land change categories: land already in agriculture in 1957 (including active and fallow); land brought into production between 1957 and 2000; land taken out of production between 1957 and 2000; and land still under forest in 2000 (Fig. 4a). Summary statistics were then extracted from each of the explanatory factors for the four change categories.

### 2.3.2. Logistic regression

To further explore the relationships made evident in this step, a regression analysis was undertaken. Because the dependent variable in this case is dichotomous (land is either converted or it isn't), logistic regression was performed with the LOGISTICREG module in Idrisi32®. First, each of the explanatory
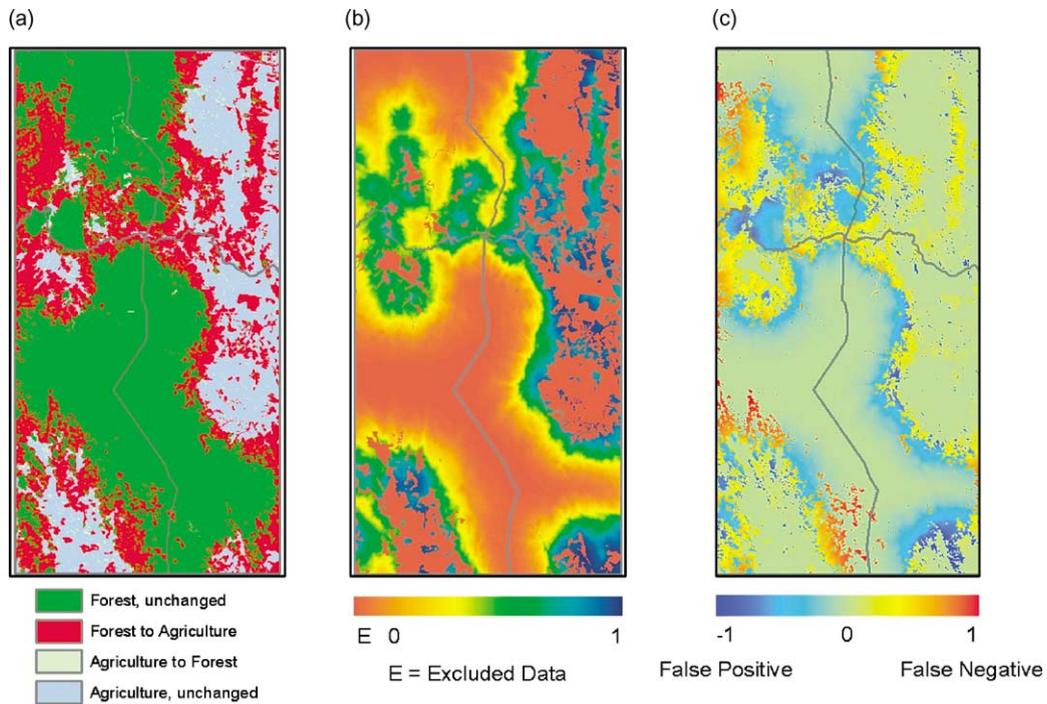
Fig. 4. Regression images: (a) Change image (cross-tabulation of 1957 and 2000 land cover maps, Fig. 2a and d); (b) Logistic regression model predicted change image. Probability expressed in a range of 0 (low) to 1 (high). Cells not candidates for conversion were excluded from the regression; (c) Logistic regression model residuals image. Residuals expressed in a range of −1 to +1, with the smallest values representing false positives (predicted to convert, but did not) and the largest representing false negatives (converted despite low probability).

factors was regressed individually using a mask to restrict the analysis to those areas that were candidates for conversion—that is, that were under forest in 1957. The strongest factors were then combined in a multiple logistic regression.

The advantage of carrying out the logistic regression *within* the GIS (rather than exporting the data to a statistical package) is that the results include not only the traditional tabular summary of statistics, but the equation is also automatically used to generate a predicted map showing the probability of each forest cell being converted to agricultural use, given the spatial configuration of the explanatory factors. It also produces a map of the residuals by subtracting the probability of change (ranging from 0 to 1) from the observed value (no change = 0; change = 1). The residuals map is particularly interesting for exploring where the model performed *least well*; those cells with large positive and negative residuals are, respectively, the false negative and false positive predictions.

### 2.3.3. Segmentation

To examine what factors might explain these patterns, a third stage of analysis was undertaken, examining the spatio-temporal patterns of land dynamics in more detail. The study area was segmented into separate landscapes, by combining the results of the regression analysis with prior knowledge of the region (Mertens and Lambin, 1997). The approach sought to assess the degree to which differential settlement processes and forest protection—and the interplay among these factors—have influenced patterns of conversion at the landscape level. The first division, north from south, was quite obvious: the national highway (RN2) that bisects the region. To the north of the RN2 lie the National Park and the Special Reserve—together the most-visited protected areas on the island—as well as the administrative offices of the park service (ANGAP) and other agencies, the railroad, the commercial center of Andasibe, and the industrial timber and mining operations. To the south of the road, while a portion of

the forest (the Maromizaha) is part of the buffer zone of the protected area complex, the bulk of the forest is in the Vohidrazana *forêt classé*, with relatively few restrictions on access or use, and little effective oversight. There is almost no extractive industry and only a minor administrative presence in these areas.

Further subdivision was done by grouping villages on either side of the two main (northern and southern) forest blocks. In the northern half of the study area, the eastern quadrant is much more isolated than its western counterpart. While the railroad follows the Sahatandra River through the eastern side, the only towns are the small rail stations of Fanovana and Ambatovola. No vehicular traffic serves the interior besides the highly irregular and unreliable trains, and colonial-era extractive ventures have left behind few traces. While virtually all of the administrative infrastructure mentioned above is found in the western quadrant, agents of the park service and the affiliated conservation projects do make periodic visits to monitor and dissuade encroachment into the Park and Special Reserve from the east.

The subdivision of the southern half of the study area follows more subtle, but nevertheless quite important, distinctions. The administrative seat (*chef lieu de canton*) of Beforona, situated along the busy RN2, lies within a 2-hour walk of the stable, long-established villages on the western side of the Vohidrazana forest. On the western side, by contrast, a road completed in the early 1990s now connects the upper reaches of the Analamazaotra River with the regional center of Moramanga, leading to immigration and facilitating commercial logging (Schoonmaker-Freudenberger, 1995). The boundaries generated by the tessellation provided a systematic logic for this east–west subdivision of the study area, and boundaries were selected that bifurcate the main northern and southern forest blocks.

### 2.3.4. Fragmentation

Fragmentation statistics were then calculated for each quadrant, for each time period, including: the proportion of the landscape under forest; size of the forest "core"; forest edge; number of forest patches; and mean patch size. Selected based on their strong analytical value in previous studies (Batistela et al., 2000; Southworth et al., 2002), these statistics can be read as the quantitative description of the land change trajectories in the four landscapes.

## 3. Results

### 3.1. Overall explanatory power of topography and demography

In the first step of the analysis, the difference between areas converted and those left in forest is quite apparent in values extracted from the elevation model, the distance from village, and distance from edge factors, by cover change category (Table 1). The analysis reveals that farmers converted low-lying land at the forest margin near their villages more readily than more distant interior land at high elevation. The slope model exhibited much less difference between land converted and that remaining in forest, a result shared by both the tessellation and potential population models.

The tabular results of the regression analysis (Table 2) amplify the summary statistics presented above. Once again, elevation, distance from village and distance from edge proved to be well correlated with the patterns of agricultural expansion, while the tessellation, the potential population models, and the slope model exhibited weaker relationships. The results of the multiple regression (bottom of Table 2) show that the model becomes moderately stronger when several factors are considered together.

### 3.2. Anomalous land changes

#### 3.2.1. Residuals

The regression analysis also generated a map of predicted conversion (Fig. 4b), as well a map of the regression residuals (Fig. 4c). In the map of residuals, the false positives (predicted to convert, but did not) often appear as large clusters, including a large still-forested ridge in the southeastern part of the study area whose conversion by a nearby village has been inhibited by its isolation behind a large river. Similarly, the western edge of the Analamazaotra Special Reserve remained intact despite topographic and demographic conditions favoring conversion. Meanwhile, the false negatives (converted despite very low probability) show up mainly as scattered patches in the forest core, mainly in the southwestern region.

#### 3.2.2. Trajectories

The fragmentation statistics for the four landscapes (Fig. 5) reveal that while general trends are evident

Table 1
Summary statistics for independent variables by change category[a]

|  | Minimum | Maximum | Mean | Standard deviation |
|---|---|---|---|---|
| Elevation model (m) |  |  |  |  |
| Converted | 260 | 1196 | 789.85 | 163.60 |
| Not converted | 301 | 1307 | 955.32 | 132.91 |
| Slope model (°) |  |  |  |  |
| Converted | 0 | 48 | 11.27 | 8.24 |
| Not converted | 0 | 49 | 11.28 | 7.97 |
| Distance from village (m) |  |  |  |  |
| Converted | 0 | 7472.17 | 1752.66 | 1152.33 |
| Not converted | 30 | 8223.50 | 4019.38 | 1816.01 |
| Gravity model (index) |  |  |  |  |
| Converted | 0.00096 | 448.29913 | 0.01673 | 0.88562 |
| Not converted | 0.00093 | 16.61477 | 0.00521 | 0.03123 |
| Distance from edge (m) |  |  |  |  |
| Converted | 30 | 8225.09 | 623.49 | 942.87 |
| Not converted | 30 | 8846.34 | 2128.70 | 1597.32 |

[a] Of the 794,857 cells that were candidates for conversion 527,219 cells were converted, while 267,638 cells were not.

that apply to all four landscapes, there are also important distinctions, and in most respects this divergence increased over time. As expected, all four landscapes exhibited a decrease in the proportion of forest, particularly since 1976, with this decline tapering off in the south and accelerating in the north after 1994. A similar effect is found in the size of the forest core, though here the southwestern landscape joined the northern areas in exhibiting a steep decline. In the northeast, the shrinkage of the core is attributable to the isolation of a large, bulbous peninsula, while the precipitous decline in the northwest's core area is related to the very small number of patches in 1957. In the southwest, the core was heavily perforated by the opening of interior gaps for agricultural fields. The patch statistics show increasing fragmentation of forest due to agricultural

Table 2
Results of logistic regression (dependent variable = conversion)

|  | Pseudo $r^2$ [a] | Adjusted odds ratio[b] | Relative operating characteristic[c] |
|---|---|---|---|
| Elevation | 0.1883 | 5.6062 | 0.78210 |
| Slope | 0.0013 | 1.0403 | 0.50370 |
| Distance from village | 0.2954 | 11.9610 | 0.84960 |
| Gravity (distance weight = 0.5) | 0.0286 | 2.6581 | 0.62220 |
| Gravity (distance weight = 2.0) | 0.1101 | 7.6712 | 0.77060 |
| Distance from edge | 0.2205 | 10.8168 | 0.83150 |
| Combined | 0.3654 | 15.1176 | 0.88150 |

[a] As is often the case with logistic regression, the pseudo $r^2$ values are rather small compared to values obtained in ordinary least squares.

[b] The odds ratio measures the success of the regression in predicting the dependent variable, based on the independent variable. In this case, it shows how often the pixels predicted to be converted were actually converted, and how often those predicted to persist in forest actually persisted. The odds are presented in the form of a ratio, yielding "a dimensionless measure, ranging from 0 to ∞, that provides an indicator of ability of the model to predict the observations to which it was fitted" (Brown et al., 2002; p. 1053). The LOGISTCREG module calculates an adjusted odds ratio, which matches the number of "converted" pixels in the predicted image to the number of "converted" pixels in the observed image (Eastman, 2001).

[c] The relative operating characteristic (ROC) assesses the validity of a model that predicts the occurrence of a class by comparing a quantitative image depicting the likelihood of that class occurring with a Boolean image showing where that class actually exists. An ROC value of 1 indicates perfect spatial agreement between the two images, while assigning likelihood at random would result in an ROC value of 0.5 (Eastman, 2001; Pontius and Schneider, 2001).
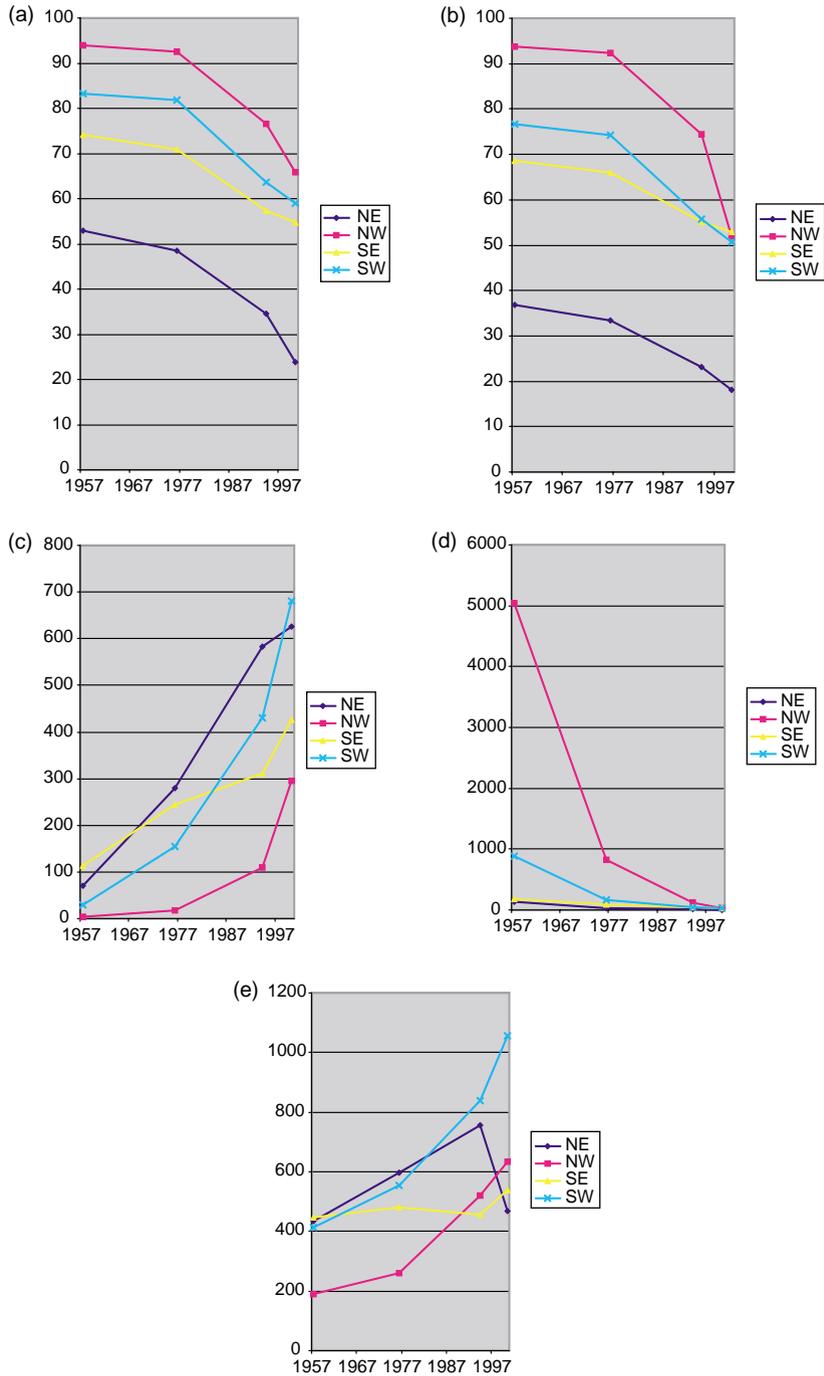
Fig. 5. Fragmentation statistics by landscape by year (1957, 1976, 1994, 2000). Quadrants: northeast (NE), northwest (NW), southeast (SE), southwest (SW). (a) Forest as a percent of each of the four quadrants, by year. (b) Core forest blocks as a percent of each of the four quadrants, by year. (c) Number of forest patches in each quadrant, by year. (d) Mean patch size in hectares in each quadrant, by year. (e) Forest edge (total length in meters) in each quadrant, by year.

clearing in all landscapes, though a notable deceleration of the decline in both the number of patches and the mean patch size is seen in the northeast after 1994. This trend in the northeast is mirrored in the dramatic shortening of forest edge there after 1994, contrary to all the other landscapes.

## 4. Discussion

### 4.1. Prior land use the strongest predictor

The results of the first and second stages of the analysis are quite intuitive. The more rapid clearing of land near village settlements is to be expected. Although temporary residences are located throughout the agricultural landscape during the *tavy* season, permanent granaries are located at the permanent village site, which also continues to be a regular meeting place throughout the year. These sites are located along permanent water courses which, by definition, are at the lowest local elevations. Likewise, forest edge plots are known to be preferred not only as a function of proximity to the village, as cultivation spreads radially from the village core, but these plots also enjoy better security for both crops (e.g., from boars and lemurs) and for people (e.g., from snakes and thieves). The correlation among these "independent" factors is reflected in the similarity of their relationships with agricultural expansion. For this reason we do not present the significance levels of the coefficients in the model, relying instead on the two measures of the predictability of the model. Rather than attempt to "work around" the obvious spatial co-dependence of these factors to parse out the effects of one or the other, their conjunctive effects were used to construct a model that highlights specific landscapes where land conversion displayed anomalous spatio-temporal patterns.

### 4.2. Slope a surprisingly weak predictor

The weak relationship between land conversion and the steepness of the land is perhaps unexpected, as this is often offered as a major explanatory factor in deforestation studies, including the landmark work of Green and Sussman (1990) in Madagascar. This may be due in part to the long (43 years) interval used in this portion of the analysis, as temporary preferences for more moderately sloping land is overwhelmed by the power of the other factors elicited above. That is, steeper lands appear to be bypassed as long as other land can be found within a reasonable distance, but forests on the steeper slopes are eventually cleared. In addition, there is very little flat land in this region, and almost all that does exist is found quite near the village sites, and was long ago converted to permanent agriculture.

### 4.3. Population "pressure" difficult to model

While the tessellation created plausible village territories, their translation into population density surfaces and the calculation of deforestation rates are quite problematic. All of the polygons created along the edges of the study area were artificially truncated by unknown and unique amounts, leading to erroneous density values. Avoiding this error would require the digitization of village centroids across considerable portions of all adjoining map sheets. Equally problematic is the extension of village territories into the remaining forest blocks, effectively lowering the population density of forest-edge villages while ceding these villages large forest "endowments," and thus extremely low rates of deforestation. There is no clear logic available for limiting this error.

Despite the use of a range of distance decay functions, the gravity models of population density failed to perform better than the simple distance-from-village factor. Two things may explain this failure: first, the link between the symbolization of structures and the actual number of houses—and therefore of their inhabitants—was imperfect, and second, the neighborhood effects of many village centroids in the northwest part of the image raised the mean local density much higher than it should have, especially since many of the structures in this landscape are actually mining and logging facilities. The simpler distance from village centroid avoids this multiplicative effect. More realistic demographic data (particularly population growth) would likely enable this factor to perform better.

### 4.4. Landscape trajectories evince institutional signatures

The interpretation of the landscape trajectories enabled the exploration of the possibility that different

restrictions—and levels of enforcement—in different parts of the study area could be detected in the spatio-temporal patterns of agricultural conversion. The most restrictive and vigorously enforced regime is found in the areas immediately surrounding the National Park and Special Reserve, and the analysis confirms that the protection afforded the core blocks *within* these areas has been quite effective, despite continued conversion of remaining forest patches. The continued conversion of forests adjacent to the protected areas in the northeast quadrant demonstrates the continuing strong demand for farm land, but this is being met by the 'cleaning up' of forest remnants previously left behind, presumably as less desirable. This can be interpreted as a 'maturation' of the landscape which, having passed through an era of rapid agricultural expansion, is now adjusting to the closing of the frontier.

The remaining quadrants continue to exhibit the characteristics of active expansion, especially the north- and southwest, with accelerating declines in the core forest blocks accompanied by increasing fragmentation (both number as size of patches, as well as length of the forest edge). These effects are further reinforced through the examination of anomalies in the residuals of the multiple logistic regression. The false negatives evince a "leapfrog" pattern—the opening of gaps in the forest interior—at higher elevations quite distant from established villages. This expansion is taking place in lesser-protected forests, and this can be interpreted as a "younger" landscape operating in a frontier mode, perhaps with the desire to "grab" land (establish a claim) prior to expected future restrictions. The instability of land tenure is confirmed in a recent report by the UN Food and Agricultural Organization on land change dynamics in Anivorano, at the heart of the southwest landscape (Schoonmaker-Freudenberger, 1995). The relatively muted response in the northwest is likely related to the presence of the National Park office, while in the southeast, a great deal of contact with development projects such as Terre Tany/BEMA may have influenced land change patterns there as well.

## 5. Conclusion

In this study, a set of inter-correlated biophysical and social factors were found to provide a great deal of explanation for the observed patterns of agricultural expansion at the level of the entire study area. Settlements are a good proxy for elevation and are very good "predictors" of conversion at the aggregate level of analysis. Not surprisingly, the best predictor of forest conversion in any given period is the location of the edge in the preceding period. Getting beyond these factors to understand the more subtle effects of differential spatio-temporal enforcement patterns is more difficult, in part because of uncertainty in other explanatory factors. In this case, signatures of land use restrictions in the agricultural landscapes of the region have been detected, using analytical techniques that are accessible to local policy-makers in their efforts to work with local communities to identify sustainable pathways to the future.

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