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MODELING DEFORESTATION AT DISTINCT GEOGRAPHIC SCALES AND TIME PERIODS IN SANTA CRUZ, BOLIVIA

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This article analyzes geo-referenced data to elucidate the relations between deforestation and access to roads and markets, attributes of the physical environment, land tenure, and zoning policies in Santa Cruz, Bolivia. It presents separate models for Santa Cruz as a whole and for seven different zones within Santa Cruz, as well as for two different time periods (pre-1989 and 1989 to 1994). The relation between deforestation and the explanatory variables varies depending on geographic scale and the zone and time period analyzed. At the department scale, locations closer to roads and the city and places that have more fertile soils and wetter climates have a greater probability of being deforested. The same applies to colonization areas. Protected areas and forest concessions are less likely to be deforested. Nevertheless, in many specific zones, these variables had no significant impact or actually had the opposite impact than in the entire department. Most of these relations were weaker between 1989 and 1994 than in the previous period.

Keywords: *Amazon; Bolivia; deforestation; frontier; agriculture development; spatial analysis; tenure systems*

1. INTRODUCTION

Research on tropical deforestation has increased rapidly during the past twenty years, but we still do not understand many aspects of where, why, and how fast forest clearing occurs. This reflects the issue's inherent complexity and limited data availability, as well as the weaknesses of available research methodologies. Recent

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literature reviews that have surveyed the approaches to modeling deforestation have emphasized the great opportunity presented by the rapidly growing availability of spatially referenced data (Lambin 1994; Kaimowitz and Angelsen 1998). Regression models that analyze such data can be especially good for looking at the relations between deforestation and explanatory variables such as access to markets, land tenure, climate, soils, topography, and zoning restrictions. These models are well suited for predicting where deforestation will occur and generally involve large samples and reasonably reliable data. Researchers can often test the models' robustness by measuring what percentage of time they correctly predict which areas will be deforested.

Previous models that look at the effects of spatially referenced explanatory variables on deforestation have shown that landholders convert more forest to agricultural use in locations with better access to markets, favorable environmental conditions, and no government restrictions on forest clearing. People are more likely to clear forests when the forests are physically closer to roads and railroads and it takes less time to reach them (Chomitz and Gray 1996; Deininger and Minten 1996; Liu, Iverson, and Brown 1993; Ludeke, Maggio, and Reid 1990; Mamingi et al. 1996; Mertens and Lambin 1997; Nelson and Hellerstein 1995; Sader and Joyce 1988; Rosero-Bixby and Palloni 1996). Similarly, forests near urban markets and villages have a higher chance of being cleared (Chomitz and Gray 1996; Mertens and Lambin 1997; Nelson and Hellerstein 1997). So do forests in areas with better soils (flat, fertile, and adequately drained) and drier climates (Chomitz and Gray 1996; Gastellu-Etchegorry and Sinulingga 1988; Sader and Joyce 1988; Rosero-Bixby and Palloni 1996). Forest fragments are more at risk than forests in large continuous areas, and those close to the forest edge are especially vulnerable (Brown, Iverson, and Lugo 1993; Liu, Iverson, and Brown 1993; Ludeke, Maggio, and Reid 1990; Mertens and Lambin 1997; Rosero-Bixby and Palloni 1996). Protected areas have a smaller probability of being deforested than nonprotected areas (Deininger and Minten 1996; Chomitz and Gray 1996). Since deforestation processes have a lot of inertia, places close to previously deforested locations are more likely to be deforested (Mertens and Lambin 2000).

This article presents the results from logistical multiple regression models that analyze the relation between deforestation and spatially referenced explanatory variables for the Department of Santa Cruz, Bolivia. It has two main objectives: (1) to provide an empirical analysis of the deforestation processes in that important region and (2) to demonstrate the potential benefits of examining deforestation at multiple geographic scales and time periods.

From a practical point of view, it is important to understand deforestation processes in Santa Cruz because forest clearing there has accelerated rapidly since the early 1990s, converting the region into one of the world's thirty-five main deforestation "hot spots" (Achard et al. 1998). Moreover, deforestation in Santa Cruz may follow quite a distinct pattern from other Latin American regions studied previously because it has more large-scale mechanized agriculture than in most of those other regions (Kaimowitz, Mendez, et al. 2002). Farmers have also cleared large areas of Brazil and Paraguay for mechanized agriculture, and the results from Santa Cruz may provide insights into deforestation in those regions.

From a methodological perspective, the article highlights the fact that explanatory variables influence deforestation in different ways depending on the particular zone, time period, and geographic scale one looks at. It compares results for pre-1989 deforestation with those for deforestation that occurred between 1989 and 1994 and compares results from models for Santa Cruz as a whole with those from seven distinct zones within Santa Cruz. This allows it to show that the same explanatory variables can appear to have quite different impacts on deforestation depending on the scale one looks at or the specific zone or time period. Previous modeling exercises of this type have largely failed to take that into account.

The article begins with a descriptive analysis of deforestation in Santa Cruz. Then it discusses the economic theory underlying deforestation models of this type and the role that scale plays in that theory. Then it present the deforestation models, including the data and methodology used and the results.

2. Deforestation in Santa Cruz, Bolivia

2.1. Basic Background Information

The Republic of Bolivia is divided into nine departments, of which Santa Cruz is the largest (see Figure 1). It includes fourteen provinces and covers 364,000 square kilometers, about one-third of the entire country (Montes de Oca 1989). Although certain portions of western Santa Cruz reach elevations of more than two thousand meters above sea level (masl), most of the department lies below five hundred masl, and geographers have traditionally classified the department as part of Bolivia's lowland tropics. The lowland tropics house the great majority of Bolivia's forest.

In 1994, Santa Cruz had 30.7 million hectares of forest. This accounted for 84.3 percent of the total territory. An additional 3.2 million hectares (8.8 percent) was in pasture or savanna, most of which is natural and has not had forest cover for a long time, if ever. Farmers used 2.1 million hectares (5.8 percent) for agriculture. Water covered most of the remaining 0.4 million hectares (Morales 1996).

As these figures suggest, historically forest clearing in Santa Cruz was limited. As recently as 1950, the entire department had less than sixty thousand hectares of cultivated land. Forest clearing slowly accelerated between 1950 and the early 1980s. The government constructed a road between the cities of Cochabamba and Santa Cruz in the early 1950s and implemented policies encouraging sugar and rice cultivation in the 1960s. In the 1970s, it provided subsidized agricultural credit. For much of the period, it also promoted settlement by large and small farmers as part of formal colonization schemes. Japanese and Mennonites made up a large portion of the large farmers involved in these schemes (Pacheco 1998). All of these policies

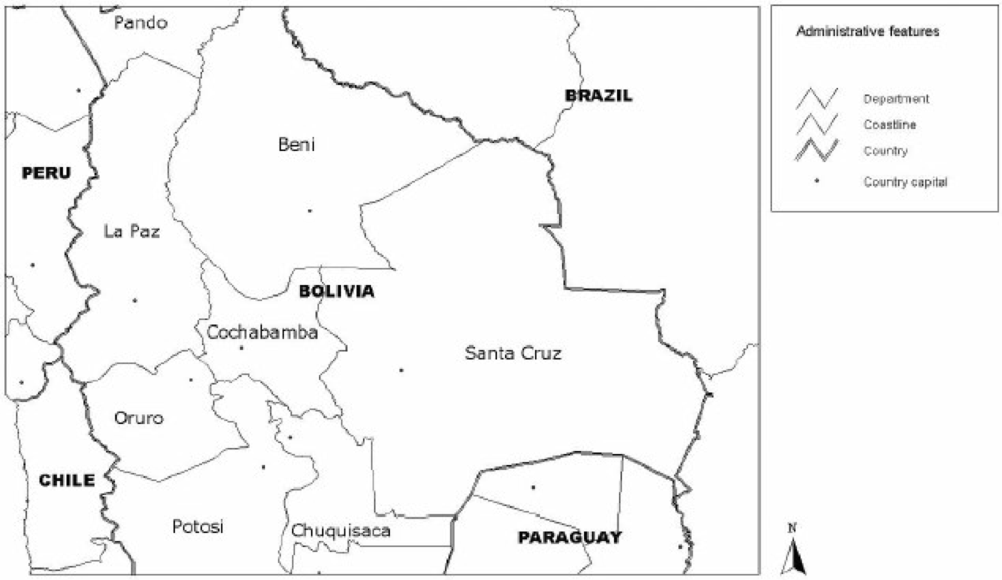

FIGURE 1. Study Area

encouraged forest clearing. Nevertheless, by international standards, the region's deforestation rates remained low.

In the past fifteen years, deforestation rates have risen rapidly. Between 1986 and 1990, Capacidad de Uso Mayor de la Tierra (CUMAT; 1992) found that the Amazonian portion of Santa Cruz (the area north of the 18° parallel) lost 38,000 hectares of forest annually. That region covers 61 percent of Santa Cruz but probably accounted for a higher percentage of forest clearing during that period. Between 1989 and 1992, deforestation in the entire department of Santa Cruz had risen to around 78,000 hectares annually. Between 1992 and 1994, annual deforestation reached 117,000 hectares (Morales 1993, 1996).

Since 1986, deforestation in Santa Cruz has occurred under distinct economic conditions and government policies. The structural adjustment policies initiated in that year have favored export production more than production for domestic consumption. There has been less government support for agricultural colonization schemes and less subsidized credit. In addition, favorable exchange rates, preferential access to the Andean Common Market, improved transportation infrastructure, and the development of the necessary technology and processing facilities have greatly stimulated soybean production (Pacheco 1998). This has led to an increase in deforestation by large-scale farmers who grow soybeans for export while discouraging forest clearing by small-scale agricultural colonists (Kaimowitz, Thiele, and Pacheco 1999).

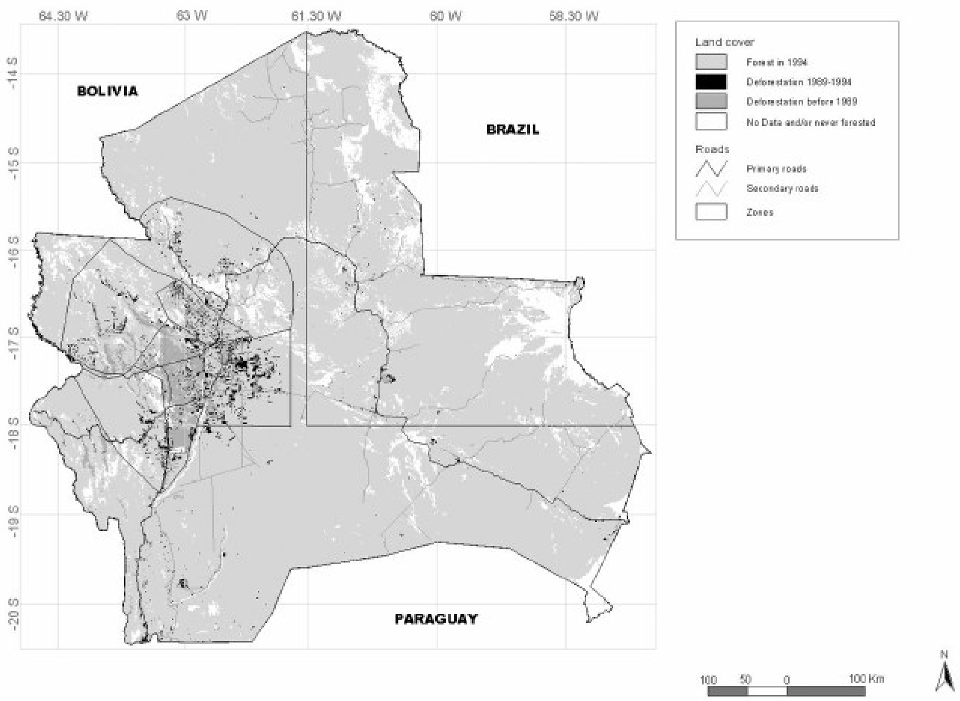

FIGURE 2. Deforestation in Santa Cruz, Bolivia (1989-94)

2.2. Data Used in the Descriptive Analysis and the Models

The remainder of this article relies heavily on the geographical information system (GIS) data sets of the Natural Resource Protection Project of the Departmental Government of Santa Cruz, the Bolivia Sustainable Forest Management Project (BOLFOR), and the Center for Research on the Management of Renewable Resources (CIMAR). This section describes those data sets.

The data sets include information on (1) land cover (1989 and 1994), (2) soil aptitude for agriculture, (3) rainfall, (4) transport infrastructure, (5) forest concessions, (6) colonization zones, and (7) protected areas. Most of the data was digitized from 1:250,000 scale maps and converted into ARC Info format.

The land cover data comes from interpretations of Landsat satellite images. It was provided in raster form, at a spatial resolution of one by one square kilometer (Morales 1993). With such low spatial resolution, one can only analyze relatively large changes in forest cover. Hence, the analysis may not fully reflect the clearing of small areas of forest for shifting cultivation. Cloud cover was minimal in the 1994 images. However, no data was available for certain parts of eastern Santa Cruz (see Figure 2).

The 1989 land cover data has separate categories for forest, agricultural land, savanna and pasture, areas with little or no vegetation, water, and urban areas. The 1994 land cover data further divides the agricultural area into traditional agriculture, commercial agriculture, anthropogenic pastures, mixed agriculture, and agriculture with forests (Morales 1996). The land cover data provides no information about forest degradation resulting from logging and other activities. It only provides information about deforestation, which involves the complete removal of forest cover. In the discussion that follows, all references to *deforestation prior to 1989* refer to the agricultural area category of the 1989 land cover data set. The assumption is that all land in agriculture in 1989 had previously been in forest. The data for the variable *deforestation between 1989 and 1994* was derived by subtracting the 1989 agricultural area from the 1994 agricultural area. The variable *distance from previous deforested areas* was computed as one-kilometer-size buffer zones from the agricultural areas in the 1989 data set.

The soil aptitude data follow the U.S. Department of Agriculture (USDA) classification scheme, which classifies land on a scale from I to VIII. Type I areas have the highest agricultural potential. Type VIII areas have the lowest potential. The classification takes into account soil fertility, depth, texture, slope, salinity, and chemical toxicity. The Natural Resource Protection Project of the Departmental Government of Santa Cruz assembled the data using secondary sources, satellite interpretation, aerial photography and observation, ground truthing, and soil sampling (Prefectura del Departamento—Consorcio IP/CES/KWC 1996).

Rainfall refers to average annual precipitation and has been divided into discrete classes by rounding off to the nearest one hundred millimeters. No information was available regarding what sources the government of Santa Cruz used to prepare its rainfall map.

The Santa Cruz Natural Resource Protection Project assembled its information on primary and secondary roads, trails, and railroads using secondary sources and ground truthing. The road data include all classified roads for the year 1993. It would have been preferable to use road data from prior to 1989 to avoid the possibility that certain roads that existed in 1993 might have been constructed in response to deforestation that occurred between 1989 and 1994 rather than the other way around. Unfortunately, no such data was available. The *trails* data include temporary roads constructed for logging and petroleum exploration.

The GIS data set includes the three protected areas with forest that existed in Santa Cruz in the early 1990s: the Amboro National Park, the Noel Kempff Mercado National Park and Biological Reserve, and the Rios Blanco y Negro Wildlife Reserve. The Bolivian government established both Amboro and Noel Kempff Mercado prior to 1989, although it expanded Amboro in 1991. The Rio Blanco and Negro Wildlife Reserve was created in 1990.

The forest concession boundaries used in the analysis were obtained from the BOLFOR GIS database and come from Bolivia's Forestry Development Center (CDF), a government agency. During the period covered, forest concessions fre-

TABLE 1. Characteristics of the Seven Defined Zones of Santa Cruz

Zone	*Type of Farmer*	*Settlement*	*Colonization*	*Soil*	*Accessibility*
1	Large, commercial	Old	Spontaneous and directed	Good	Good
2	Large, commercial	New	Spontaneous and directed	Good	Good but recent
3	Small	Old	Directed	Medium	Good
4	Small	Old	Directed	Good	Mixed
5	Small	New	Spontaneous	Poor	Mixed
6	Small	Mixed	Directed	Poor	Mixed
7	Ranchers	Mixed	Spontaneous	Medium	Poor

quently overlapped with other types of property, including private land holdings, mining concessions, and even protected areas. Most of the forest concessions were granted before 1989.

Santa Cruz has government-sponsored small-farm colonization zones and Mennonite and Japanese agricultural colonies, populated by larger farmers. The colonization zone data include both and comes from a map CIMAR produced. The map has a scale of 1:1,000,000 and should be considered a first approximation (de Vries 1994).

2.3. *Deforestation Trends in Seven Selected Zones of Santa Cruz*

For the purposes of this study, the authors divided a portion of the department of Santa Cruz into seven separate zones based on the type of farmer (large, small), production system (agriculture, ranching), and settlement patterns (spontaneous or directed settlement, new or old). The seven zones are the (1) commercial integrated zone, (2) southern expansion zone, (3) northern expansion zone, (4) northwestern colonization zone, (5) northern colonization zone, (6) western colonization zone, and (7) eastern ranching zone (see Table 1 and Figure 3).

The first six zones, which fall within a radius of approximately two hundred kilometers from the city of Santa Cruz, cover only 20 percent of the department's total area, but together they accounted for 78 percent of total deforestation between 1989 and 1994. The average annual rate of deforestation in these zones during that period was 1.5 percent, almost five times higher than the departmental average, which was 0.33 percent for the same period (Morales 1993, 1996).

The rest of the department, which includes zone 7 and areas not included in any of the seven zones, has a very low deforestation rate of less than 0.1 percent of forest loss per year. The authors modeled zone 7 separately because it seemed important to compare the factors influencing deforestation in a low deforestation/ranching area with those that affect in the higher deforestation, more agricultural, zones. No

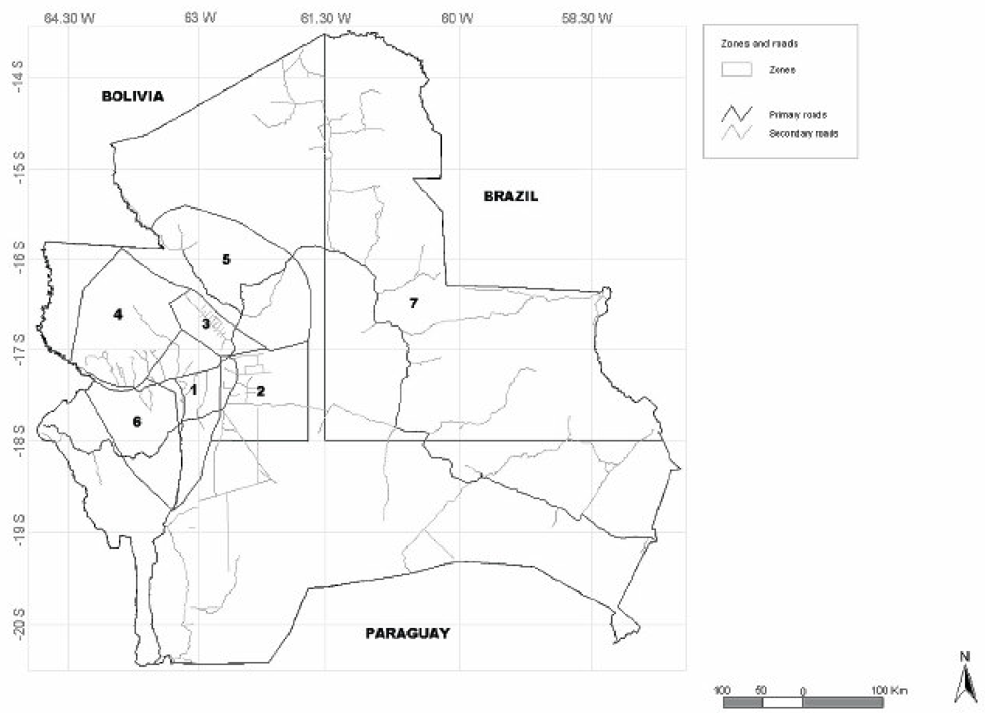

FIGURE 3. Subregions (Zones) Considered

separate model was developed for the 51 percent of the department outside the seven zones. Not only does it have extremely low deforestation rates, but the great diversity in the social processes and production systems in these areas would have made it difficult to interpret the results. The areas left out of the seven zones include the Chaco region to the south and the area southwest of the city of Santa Cruz. Annual precipitation in the Chaco often falls below eight hundred millimeters. Dry forest and scrub makes up a large portion of the natural vegetation in that region, and the arid climate discourages crop production. Steep slopes limit agricultural development in the area southwest of the city of Santa Cruz. That area has some of the department's oldest settlements but lacks economic dynamism and has a poor road network (Davies 1994).

Zone 1 (commercial integrated zone). The commercial integrated zone constitutes Santa Cruz's traditional center of large-scale commercial agriculture and was one of the earliest areas to undergo large-scale deforestation. Farmers had already cleared a large portion of its forest by 1980. It has good soils and a favorable climate, as well as the department's most developed transportation infrastructure and its largest market. More than a quarter of the area in this zone lies less than five kilometers from a primary road. Large farms owned by both native-born Bolivians and Japanese and Mennonite farmers that settled in the government-sponsored colonization schemes dominate the area (Pacheco 1998). In the 1970s, the farmers grew mostly sugar cane, maize, cotton, and sorghum and grazed cattle. More recently, cotton has declined, while wheat and soybeans have emerged as major crops (Camara Agropecuaria del Oriente [CAO] 1996). Between 1989 and 1994, this zone had the highest annual deforestation rate, measured as a percentage of the remaining area in forest. However, the absolute amount of forest clearing was only a fraction of that found in the following zone (see Table 2). As a result of the widespread deforestation over the years, the great majority of the remaining forest is close to previously deforested areas, the so-called forest edge.

Zone 2 (southern expansion zone). Following the mid-1980s, the major focus for forest clearing in Santa Cruz shifted eastward from the commercial integrated zone to the southern expansion zone. This zone had by far the highest absolute level of deforestation between 1989 and 1994 (see table 2). Large-scale farmers cleared big blocks of land, mostly for mechanized soybean and wheat production. The zone has an excellent climate and the soils are good for growing soybeans, although they are fragile and easily susceptible to compaction and wind erosion (Kaimowitz, Thiele, and Pacheco 1999). Poor access to markets and the fact that there were still cheap and fertile lands available closer to Santa Cruz limited expansion into this zone prior to the mid-1980s. Since then, the Bolivian government has greatly improved the road network in the area and given out large land grants to wealthy farmers, and it has become increasingly expensive to purchase land in the integrated commercial zone. In addition, the exchange rate devaluation in the mid-1980s and technological progress in soybeans encouraged the expansion of mechanized soybean production in this area, which was particularly suited for the crop (Kaimowitz, Thiele, and Pacheco 1999). As a result, forest clearing advanced rapidly eastward.

Zone 3 (northern expansion zone). This area lies northwest of the southern expansion zone. Government road building and agricultural colonization schemes promoted small-farmer settlement there in the 1970s. More than 60 percent of all the land in this zone forms part of colonization zones, and these zones account for an even higher percentage of total deforestation (see Table 3). As a result, forest clearing follows the classic fish-bone pattern along the secondary roads. Since the 1970s, spontaneous migration to the area has continued, and has extended beyond the original colonization zones. As late as 1989, 75 percent of the zone was still forested, but between 1989 and 1994, forest clearing proceeded extremely rapidly. By 1994, only 64 percent of the land still had forest cover. Most of the farmers practice shifting cultivation and grow rice as their main crop.

Zone 4 (northwestern colonization zone). Colonization schemes represent only 13.2 percent of the total area in this zone. Nevertheless, the zone includes some of the oldest and most successful small-farm agricultural colonization schemes, dating back to the early 1960s (Thiele 1995; Pacheco 1998). Spontaneous migration

TABLE 2. Forest and Forest Cover Changes in Santa Cruz in the Seven Defined Zones and Outside the Zones

Zone	*Total Area (square kilometers)*	*Forest 1989 (square kilometers)*	*Percentage of Land in Forest (1989)*	*Forest 1994 (square kilometers)*	*Percentage of Land in Forest (1994)*	*Total Deforestation 1989-94 (hectares)*	*Rate of Deforestation (annual percentage of forest cover)*
1	9,367	3,267	34.9	2,596	27.7	67,100	4.1
2	12,041	10,578	87.8	8,999	74.7	157,900	3.0
3	4,221	3,170	75.1	2,692	63.8	47,800	3.0
4	15,699	12,519	79.7	12,061	76.8	45,800	0.7
5	21,386	16,782	78.5	16,387	76.6	39,500	0.5
6	10,454	8,584	82.1	8,193	78.4	39,100	0.9
7	105,871	86,036	99.3	85,717	98.8	31,900	0.1
Outside zones	185,576	173,366	99.1	172,587	98.7	77,900	0.1
Total	364,615	314,459	86.2	309,342	84.4	511,700	0.3

TABLE 3. Colonization Zones and Deforestation

Zone	*Percentage of Total Area in Colonization Zones*	*Percentage of Deforested Area in Colonization Zones, pre-1989*	*Percentage of Deforested Area in Colonization Zones, 1989-94*
1	33.2	34.3	37.3
2	20.0	48.5	28.5
3	62.5	76.1	70.7
4	13.2	34.5	9.6
5	0.5	1.3	0.8
6	12.1	17.7	7.7
7	0.0	0.0	0.0
Santa Cruz	3.3	29.3	22.2

TABLE 4. Forest Concessions and Deforestation

Zone	*Percentage of Total Area in Forest Concessions*	*Percentage of Deforested Area in Forest Concessions, pre-1989*	*Percentage of Deforested Area in Forest Concessions, 1989-94*
1	0.0	0.0	0.0
2	1.0	0.1	0.0
3	2.3	0.4	3.3
4	75.0	37.7	79.0
5	75.1	68.9	72.4
6	2.6	5.2	0.3
7	45.0	13.6	14.7
Santa Cruz	43.0	11.0	17.6

followed these schemes in the 1970s. It is a humid region with fertile soils, where rice does well. Other crops and livestock have become more important as the small farmers have become more capitalized over time. Access to primary and secondary roads in this zone is poorer than in the other zones near Santa Cruz. In recent years, the annual deforestation, measured as a percentage of total forest area, has been has been much lower in this zone than in the previously mentioned zones, although a significant amount of forest has been lost nonetheless. Much of the forest loss has been within forest concessions, particularly the El Chore Forest Reserve, where there have been many conflicts between timber companies and spontaneous migrants. Between 1989 and 1994, fully 80 percent of all deforestation occurred in forest concessions (see Table 4).

TABLE 5. Protected Areas and Deforestation

Zone	*Percentage of Total Area in Protected Areas*	*Percentage of Deforested Area in Protected Areas, pre-1989*	*Percentage of Deforested Area in Protected Areas, 1989-94*
1	1.0	0.3	2.2
2	0.0	0.0	0.0
3	0.0	0.0	0.0
4	0.0	0.0	0.0
5	0.0	0.0	0.0
6	39.3	2.0	1.5
7	7.6	0.0	0.3
Santa Cruz	7.9	0.3	0.6

Zone 5 (northern colonization zone). This area has been settled more recently than the previously mentioned zones and with less government support. It tends to have poorer soils. In part as a result, it has the lowest deforestation rate as a percentage of total forest of any of the four colonization zones. Forest still covered 76.6 percent of the area in 1994. Forest concessions account for fully three-quarters of the zone's area (see Table 4).

Zone 6 (western colonization zone). This zone has some small-farm colonization zones, but they only cover 12 percent of the total area. The soils are poor. The Amboro National Park covers almost 40 percent of the entire zone (see Table 5). Amboro has been the subject of conflict between local farmers and government authorities. Even so, less than 2 percent of all the deforestation in the zone has occurred within the protected area.

Zone 7 (eastern ranching zone). Moving east from the expansion zone, one hits the "Brazilian" shield, characterized by infertile and acidic soils. Cattle ranching and logging are the main activities there, although some small-farm agriculture exists. During the period under study, a large portion of the land was in timber concessions. Ranchers have cleared a moderate amount of forest for pasture, but it is difficult to distinguish these areas from natural savanna in the satellite images.

2.4. Additional Descriptive Statistics about Deforestation in Santa Cruz

Government-sponsored colonization zones cover only 3 percent of Santa Cruz but account for 20 percent of all deforestation (see Table 3). Zones 1, 2, and 3 include the majority of colonization zones. A large proportion of the colonization area had already been deforested prior to 1989. Nevertheless, large areas of forest continued to be lost in these areas between 1989 and 1994.

TABLE 6. Deforestation and Distance from Santa Cruz, 1989-94 (in percentages)

Zone	*0-50 km*	*50-100 km*	*100-150 km*	*150-200 km*	*>200 km*
1	63.0	31.6	5.4	0.0	0.0
	(71.1)	(22.5)	(6.4)	(0.0)	(0.0)
2	2.7	65.9	31.4	0.0	0.0
	(2.5)	(46.5)	(49.0)	(2.0)	(0.0)
3	0.0	86.0	14.0	0.0	0.0
	(0.0)	(87.6)	(12.4)	(0.0)	(0.0)
4	4.1	48.9	45.4	1.5	0.0
	(4.8)	(38.7)	(48.8)	(7.6)	(0.0)
5	0.0	6.8	41.0	50.1	2.0
	(0.0)	(1.0)	(33.3)	(57.7)	(7.9)
6	12.0	78.5	9.5	0.0	0.0
	(16.6)	(64.0)	(19.4)	(0.0)	(0.0)
7	0.0	0.0	0.0	0.7	99.3
	(0.0)	(0.0)	(0.0)	(4.4)	(95.6)
Santa Cruz	10.4	45.5	21.1	6.0	16.9
	(2.6)	(7.3)	(10.8)	(12.4)	(66.7)

Note: Values shown represent total deforested area within the zone located less than a certain distance from Santa Cruz. Values in parentheses correspond to total area of each zone located within the same distance threshold.

As of 1989, 43 percent of the land in the department was in forest concessions (see Table 4). These were mainly located far from the city of Santa Cruz in the north, northwest, and eastern parts of the department (zones 4, 5, and 7). About 17 percent of all deforestation has occurred in forest concession areas, most of which is concentrated in zones 4 and 5, to the north and northwest of the city of Santa Cruz. In fact, in these two zones, more than 70 percent of all deforested areas are located within forest concessions. Protected areas cover approximately 8 percent of the department, but only 1 percent of the total deforestation has taken place within these areas (see Table 5).

Almost 56 percent of total deforestation in the period from 1989 to 1994 occurred less than one hundred kilometers from the city of Santa Cruz (see Table 6). Although less than 20 percent of all land in Santa Cruz was within five kilometers of a previously forested area that had been cleared for agriculture, almost 80 percent of the deforestation during that period was in those areas (see Table 7).

Only 10.5 percent of the land in Santa Cruz is less than ten kilometers from a primary road. Still, 30.5 percent of the deforestation between 1989 and 1994 was in such areas. This relation does not apply, however, to zones 1, 2, and 3, which have already lost a fair portion of their forest and experienced the highest rates of deforestation during that period. Most of the land in these zones close to primary roads that has favorable characteristics for agriculture had already been deforested prior to 1989, and that may explain this seemingly contradictory result (see Table 8).

TABLE 7. Deforestation in Santa Cruz and Distances from the Forest/Nonforest Edge, 1989-94 (in percentages)

Zone	*0-2.5 km*	*2.5-5 km*	*5-7.5 km*	*7.5-10 km*	*>10 km*
1	90.3	9.7	0.0	0.0	0.0
	(94.5)	(4.8)	(0.6)	(0.0)	(0.0)
2	44.9	25.8	13.0	7.7	8.7
	(32.9)	(17.5)	(10.8)	(8.3)	(30.4)
3	87.2	12.5	0.2	0.0	0.0
	(79.0)	(16.5)	(3.2)	(1.0)	(0.2)
4	45.4	26.2	17.2	6.8	4.4
	(31.4)	(15.4)	(10.9)	(8.4)	(33.9)
5	63.8	19.5	7.3	6.3	3.0
	(21.2)	(16.9)	(13.0)	(11.0)	(37.8)
6	76.2	19.7	2.8	0.3	1.0
	(32.1)	(22.2)	(13.0)	(9.0)	(23.6)
7	48.0	15.1	9.2	8.2	19.4
	(4.8)	(6.7)	(7.4)	(7.9)	(73.2)
Santa Cruz	59.8	19.8	8.3	4.6	7.4
	(11.6)	(7.5)	(6.3)	(6.1)	(68.5)

Note: Values shown represent total deforested area within the zone located less than a certain distance from the forest/nonforest. Values in parentheses correspond to total area of each zone located within the same distance threshold.

TABLE 8. Deforestation in Santa Cruz and Distances from Primary Roads, 1989-94 (in percentages)

Zone	*0-5 km*	*5-10 km*	*10-15 km*	*15-20 km*	*>20 km*
1	21.9	21.5	20.1	15.6	20.9
	(26.7)	(20.9)	(16.6)	(13.7)	(22.1)
2	9.7	6.3	8.9	8.3	66.7
	(8.1)	(6.3)	(5.4)	(4.7)	(75.5)
3	13.6	9.0	8.6	21.1	47.7
	(10.3)	(10.6)	(13.5)	(14.6)	(51.0)
4	3.5	9.6	6.1	7.6	73.1
	(4.5)	(3.0)	(3.2)	(3.5)	(85.9)
5	23.3	21.0	27.8	11.4	16.5
	(10.4)	(10.1)	(10.4)	(9.6)	(59.5)
6	48.3	25.8	13.8	7.2	4.9
	(18.9)	(18.4)	(16.7)	(14.8)	(31.2)
7	25.0	7.9	16.8	11.2	39.1
	(4.3)	(3.9)	(3.8)	(3.9)	(84.0)
Santa Cruz	19.1	11.6	11.9	10.1	47.3
	(5.6)	(4.9)	(4.8)	(4.5)	(80.1)

Note: Values shown represent total deforested area within the zone located less than a certain distance from a primary road. Values in parentheses correspond to total area of each zone located within the same distance threshold.

TABLE 9. Deforestation in Santa Cruz and Distances from Secondary Roads, 1989-94 (in percentages)

Zone	*0-5 km*	*5-10 km*	*10-15 km*	*15-20 km*	*>20 km*
1	17.1	27.9	26.8	10.3	17.9
	(36.3)	(25.5)	(14.6)	(9.1)	(14.5)
2	63.0	20.2	6.8	4.7	5.3
	(42.3)	(20.2)	(11.0)	(8.5)	(18.0)
3	56.5	28.4	12.5	2.3	0.2
	(43.1)	(27.5)	(15.7)	(9.9)	(3.8)
4	29.3	26.0	16.2	10.0	18.6
	(24.3)	(14.5)	(10.5)	(9.1)	(41.6)
5	13.7	21.0	18.2	11.9	35.2
	(9.1)	(10.1)	(12.5)	(11.7)	(56.4)
6	2.6	3.6	1.3	0.3	92.3
	(8.4)	(6.0)	(6.8)	(7.7)	(71.0)
7	38.5	6.9	12.5	9.5	32.6
	(15.0)	(13.6)	(13.7)	(13.7)	(43.9)
Santa Cruz	39.7	20.1	12.5	6.9	20.9
	(15.3)	(12.0)	(10.8)	(9.9)	(52.1)

Note: Values shown represent total deforested area within the zone located less than a certain distance from a secondary road. Values in parentheses correspond to total area of each zone located within the same distance threshold.

A similar pattern seems to apply with regard to deforestation and distance from secondary roads. In general, the closer one is to a secondary road, the higher the probability of deforestation. Nevertheless, this relation is weaker or nonexistent in the case of zones 1, 2, and 3, which have already experienced substantial deforestation (see Table 9).

Most of the forest cleared between 1989 and 1994 was located in areas with class III to V soils, rather than on poorer soils, which are less suited for agriculture (see Table 10.) Similarly, there was little deforestation in the most arid and wetter areas. Forest clearing has been concentrated in areas with medium rainfall (eight hundred to one thousand millimeters per year), which are optimal for soybean production.

3. Regions and Time Periods as Units of Analysis in Spatial Deforestation Models

Most previous studies of deforestation that use spatial data have failed to acknowledge that the same geo-referenced explanatory variables can influence deforestation in different ways depending on the subregion of the study area and the specific time period one looks at. This section discusses why such differences might occur.

The economic theory underlying practically all models of this type is that a farmer will deforest an area whenever the benefits outweigh the costs. Since both

TABLE 10. Deforestation in Santa Cruz and U.S. Department of Agriculture Soil Type, 1989-94 (in percentages)

Zone	*II*	*III*	*IV*	*V*	*VI*	*VII*	*VIII*
1	0.0	48.0	37.8	10.4	3.6	0.1	0.0
	(0.0)	(57.4)	(29.2)	(5.4)	(6.9)	(1.1)	(0.0)
2	1.8	63.3	5.1	29.8	0.1	0.0	0.0
	(4.6)	(65.2)	(3.5)	(23.6)	(2.6)	(0.5)	(0.0)
3	2.5	6.1	4.2	87.2	0.0	0.0	0.0
	(2.9)	(12.0)	(4.1)	(76.1)	(0.1)	(4.8)	(0.0)
4	0.0	29.9	40.2	12.9	11.8	5.2	0.0
	(3.3)	(30.5)	(34.7)	(10.2)	(8.9)	(12.4)	(0.0)
5	7.9	8.6	5.1	19.8	33.3	25.2	0.0
	(3.6)	(10.0)	(14.5)	(8.3)	(42.4)	(21.2)	(0.0)
6	0.0	0.5	28.7	0.5	5.1	51.5	13.6
	(0.0)	(1.4)	(9.0)	(0.6)	(9.2)	(36.1)	(43.7)
7	0.0	0.0	45.4	9.9	35.4	8.6	0.7
	(0.0)	(1.1)	(39.6)	(8.1)	(39.2)	(11.2)	(0.7)
Santa Cruz	1.9	34.0	18.8	23.6	10.1	10.1	1.5
	(0.9)	(12.5)	(28.1)	(11.0)	(32.6)	(10.9)	(4.0)

Note: Values shown represent total deforested area within the zone with land of that U.S. Department of Agriculture soil type. Values in parentheses correspond to total area of each zone with soil of that type.

the benefits and costs accrue over time, model makers convert both into net present values using some discount rate. The potential benefits from deforestation come from the revenues earned from agriculture. One would expect that deforesting a location with soils, climates, and topography more favorable for farming would provide higher agricultural revenues than deforesting less favorable areas. Costs include all of the costs associated with agricultural production (including forest clearing), transportation costs, and the opportunity costs associated with no longer being able to use the land to extract forest products. When government zoning variables such as protected areas, forest concessions, and colonization areas are included in the analysis, this implies that farmers may either get additional benefits from deforesting in certain areas (colonization zones) or have to pay additional costs for doing so (protected areas and forest concessions).

Since in practice the only explanatory variables in these models include transportation costs, land suitability, and government zoning categories, it is implicitly assumed that all other potential explanatory variables do not vary within the area analyzed and/or are independently distributed from the explanatory variables used in the model. Most model makers would acknowledge that variables such as prices, economies of scale, presence of processing infrastructure, the specific environmental requirements of different production systems, farmer knowledge and resource endowment, social capital, and the level of enforcement of regulations influence deforestation decisions and vary over time and space. However, they generally cannot directly include these factors in their models due to lack of data, and they implicitly assume these variables are not correlated with the variables they do include. At best, they may test for spatial or temporal autocorrelation, but such tests only take into account a limited set of possible systematic interactions between the variables and space and time.

As the models presented below show, when one analyzes data from distinct subregions or over different time periods, often it turns out that the coefficients on the regression equations are different at statistically significant levels. Similarly, variables that appear important at larger scales may not appear relevant at smaller scales and vice versa (Walsh et al. 1997; Veldkamp and Fresco 1997). This can occur for various reasons. The variables mentioned in the previous paragraph vary over time and space and may be correlated with the explanatory variables included in the model. In some places, times, or scales, there may not be sufficient variation within the explanatory variables to assess the statistical relation between the explanatory variables and deforestation, so the coefficient on the variable shows up as statistically insignificant.

Traditional models tend to assume that observed relations are in equilibrium, that is, that farmers have adjusted completely and moved to their optimal land use positions. In practice, farmers adopt slowly, due to resource constraints and imperfect information. Hence, the relations between deforestation and spatial explanatory variables may differ depending how long the deforestation process has been underway. If there are missing variables that explain why certain areas are not deforested, these may become relatively more important once only small areas of forest remain.

The specific subregions used for this study were designed to take into consideration the type of farmer (large/small, spontaneous migrant/government-supported migrant, rancher/crop producer), the availability of nontransportation infrastructure, and the duration of settlement. The authors hypothesize that these variables tend to be grouped in nonrandom ways across the landscape and correlate with some of the explanatory variables included in the model. Thus, for example, larger farmers in Santa Cruz may tend to look for large areas appropriate for mechanized soybean and wheat production where there is already processing infrastructure available in the area. This will be associated with one pattern of deforestation. In contrast, small farmers in directed settlement programs may look for areas more appropriate for slash-and-burn rice production, which would be associated with a distinct pattern of deforestation. Thus, for example, previous work by Mertens and Lambin (1997) has shown that in peri-urban contexts, forest clearing exhibits a circular pattern around the towns, and distance to towns and roads strongly affects forest clearing but proximity to forest edge does not. Along roads, there is a “corridor” pattern of deforestation where proximity to roads and forest edges are significant determinants of forest clearing but distance to towns is not. Finally, in areas where diffuse shifting cultivation dominates, proximity to forest edge increases the probability of forest clearing, whereas distance to roads and towns is less important.

Looking at multiple time periods allows one to take into account both price and policy changes. Previous models have ignored these variables. There is limited variation in prices across space that is not linked to transport costs, so one-period models cannot usually say much about price effects. Similarly, one needs at least two periods to look at the impact of policy changes on how the other explanatory variables influence deforestation.

4. The Models

4.1. The Variables, the Econometrics, and the Sample

The models constructed are logistical multiple regression (LMR) models whose dependent variable is the presence or absence of deforestation in a particular location during the time period considered. The independent variables are (1) *accessibility:* distance from roads, trails, Santa Cruz, and previously deforested areas; (2) *land tenure and zoning policies:* presence or absence of colonization zones, concessions areas, and protected areas; and (3) *ecological conditions:* rainfall and soil aptitude for agriculture.

LMR is designed to estimate the parameters of a multivariate explanatory model in which the dependent variable Y is categorical (dichotomous in this case), and the independent variables X_n are either continuous or categorical. The general LMR equation is

$$Logit(p) = \log\left[\frac{p}{1-p}\right] = \alpha + \beta_1 X_1 + \beta_2 X_2 + \ldots + \beta_n X_n \qquad (1)$$

where p is the probability of having deforestation $Pr(Y = 1)$ and α and β_n are the coefficients to be estimated.

The computed LMR equations and associated statistics allow us to characterize the role and importance of the explanatory variables in determining whether a particular state of the dependent variable occurs, in this case whether a specific location was deforested during the period in question. A set of explanatory variables X_n characterizes each location, or *observation*, for the specific period. Each observation corresponds to a 1×1 kilometer pixel or point. Such observations are the equivalent of individual households in a traditional regression analysis based on a sample of households. Equation 1 gives the probability of each location being deforested as a function of its attributes. One can interpret the results of the LMR analysis in terms of logit, that is, the log of the probability of having deforestation instead of forest (Menard 1995; Hosmer and Lemeshow 1989).

LMR has a number of advantages compared to simply analyzing descriptive statistics, as in section 2.4. In particular, it allows one to separate out the role of each variable and to quantify its relative contribution. Simply juxtaposing one independent variable with the dependent variable without taking into account the others can give a very distorted impression. Thus, for example, deforestation may correlate highly with distance from Santa Cruz, but this may be because areas close to Santa Cruz have better soils, not because they are closer to large markets as our accessibility hypothesis implies.

As mentioned previously, the models examine the proximate causes of deforestation in two successive time periods: (1) before 1989 and (2) from 1989 to 1994. The only reliable information available on deforestation per se is for the 1989 to 1994 time period. For the period prior to 1989, the models use agricultural areas in the 1989 land cover map as a proxy for deforestation. Kummer and Sham (1994) argued that it is inappropriate to use land use data for a single period as a proxy for deforestation because lands that presently lack forest may never have had forest and the factors that influenced deforestation in the distant past may be quite different from those currently causing deforestation. These arguments only partially apply in this case because the models were estimated with a data set that eliminated all the areas that probably never had forest cover, and most deforestation prior to 1989 was between 1950 and 1989, not in the distant past.

For each of the two time periods, the authors computed several models, first for the entire Department of Santa Cruz (except those areas with cloud cover) and second for the seven zones described above. The data used to estimate the models comes from a random sample of the 1×1 kilometer pixels in the GIS data set from the Santa Cruz Natural Resource Protection Project. The sample included 33 percent of the total observations in each case. That made it possible to work with a large and representative sample of more than one hundred thousand observations for the entire Department of Santa Cruz and between one thousand and seventeen thousand observations for each of the seven zones.

Three common statistical problems in models such as these are spatial autocorrelation, multicollinearity, and endogeneity.

Spatial autocorrelation. This can obscure the results of a regression analysis. Deforestation as a phenomenon is likely to be characterized by spatial autocorrelation, which in general results in inefficient parameter estimates and inaccurate measure of statistical significance. Spatial autocorrelation was estimated by Moran's I statistic for a range of distance separating the observations (sample points). Results indicate the presence of autocorrelation at the most detailed resolution and a rapid decrease at larger separation distance: for both the entire data set and the sample data used in this article, the values of the Moran's I statistic for the independent variable are, respectively, .713 and .21. Therefore, the use of sampling has allowed to minimize the potential spatial autocorrelation effects.

Multicollinearity. Independency between explanatory variables is a prerequisite of the statistical method used. Variables such as distance to roads and markets and soil quality tend to be highly correlated: this can make it difficult to distinguish their separate effects. We tested for collinearity in our independent variables at both the level of Santa Cruz and in the individual zones by looking at the coefficient of determination (R^2) between all pairs of variables and found a weak association between explanatory variables (except for one pair, all values are smaller than .4). That implies a relatively low degree of collinearity. The highest value of R^2 (.516) was found between the variables *distance from previously deforested areas* and *distance from roads*. Separate models were built with and without one of these two variables (see section 4.2).

Endogeneity. The endogeneity problem arises because it is hard to distinguish situations where human settlements, productive activities, and infrastructure are located in certain places because those places have environmental conditions that make them good to deforest from those where deforestation occurs because people settle, build roads, or make specific zoning decisions. We have attempted to reduce this problem by controlling for agricultural suitability and using independent variables from a time period prior to the dependent variables.

4.2. The Results

Table 11 presents the results of the LMR analyses of deforestation for the entire Department of Santa Cruz. The authors ran one model for deforestation prior to 1989 and two models for the period 1989 to 1994. The first of the 1989 to 1994 models, model A, leaves out the explanatory variable *distance from previously deforested areas*. Since that variable could not be included in the pre-1989 model, leaving it out in the 1989 to 1994 model makes the models for the two periods more comparable. Moreover, it allows us address the issue of collinearity between this variable and the variable *distance from roads*. The second model, model B, includes *distance from previously deforested areas* as an explanatory variable.

All three models presented in Table 11 were statistically significant at the p = .001 level. All the estimated coefficients of the explanatory variables have the expected sign, and they were all statistically significant, except for whether an observation is located in a colonization zone, which was not statistically significant between 1989 and 1994. Wetter areas and areas with better soils have more deforestation, although the rainfall coefficient ceased being significant in the second model for the 1989 to 1994 period. Areas close to roads, trails, the city of Santa Cruz, and other previously deforested areas are also more likely to be deforested. Even after taking into account soil quality, rainfall, and accessibility, colonization zones suffered more deforestation (prior to 1989) and forest concessions and protected areas experienced less deforestation. Including the variable *distance from previous deforested areas* in model B did not modify the sign of the coefficients, although in general, the size of the coefficients decreased.

A number of coefficients became smaller in the second period compared to the first. Location in a protected area or forest concession provided less effective protection from deforestation in the second period, and as noted previously, being in a

TABLE 11. Results of the Logistical Regression Analysis for Deforestation in the Department of Santa Cruz prior to 1989 and between 1989 and 1994

Variable	*Before 1989*	*1989-94, Model A*	*1989-94, Model B*
COLO[a]	0.2471***	n.s.	n.s.
CONC[a]	–0.8816***	–0.6605***	–0.2604***
PROT[a]	–2.5906***	–1.3428***	–0.7408**
PREC	0.0004***	0.0002**	n.s.
DIST_NF	—	—	–0.1888***
ROAD_M	–0.0293***	–0.0222***	–0.0060***
ROAD_S	–0.0179***	–0.0100***	0.0046*
TRAILS	0.0043**	–0.0313***	–0.0253***
DIST_SC	–0.0144***	–0.0084***	–0.0046***
SOIL[b]			
II	0.5515***	0.3974*	n.s.
III	0.7591***	0.5283***	0.6145***
IV	0.5171***	0.2628***	0.2163***
V	–0.1957***	0.5864***	0.6721***
VI	n.s.	–0.6257**	–0.6089***
VII	–0.3182***	–0.1935*	–0.2614***
VII	–1.3992***	–0.9557***	–0.9037***

a. Dichotomous (presence/absence) independent variable, absence being the reference category.
b. More than two-values categorical independent variable; the effect of each category is compared to the overall effect.
*p = .05. **p =.01. ***p = .001.

colonization zone ceased to be associated with higher deforestation rates. The influence of access to roads and markets, precipitation, and soil quality also declined. The only exception to this was distance to logging and mining trails, which only became significant after 1989. Interestingly, category V soils, which were less likely to be deforested than other soils prior to 1989, became more likely to be deforested in the following period. This probably relates to the fact that the regions that experienced a lot of expansion of mechanized soybean production have a lot of that type of soil. Presumably, these areas had processing infrastructure, specialized services, and other attributes appropriate for soybean production that the models do not fully capture.

Changes in context and selection bias seem to explain many of the differences between the two time periods at the Santa Cruz level. In the case of colonization zones, for example, prior to 1989, the Bolivian government provided large amounts of credit, social services, and other assistance in these areas. That undoubtedly attracted many farmers. This was particularly true prior to 1985, before the government implemented its structural adjustment program. In contrast, after 1989, colonization zones received little government support and, hence, probably had less influence on land use. Similarly, the structural adjustment policies of the late 1980s and early 1990s favored large-scale soybean production for export over small-scale production of domestic food crops (Kaimowitz, Thiele, and Pacheco 1999). As noted previously, soybeans were grown more on lower-potential category V soils. In addition, the optimal precipitation for soybean production was lower than for rice production. Hence, it is logical that the correlation between deforestation and wetter areas declined as the main production system involved in deforestation changed. With regard to selection bias, some of the areas with goods soils, favorable rainfall, access, and no zoning restrictions that had not already been deforested by 1989 probably have unobserved attributes that made them less likely to be deforested in the subsequent period.

Table 12 presents the results of the LMR analyses of deforestation for each of the zones for deforestation between 1989 and 1994. All the regression models analyzed were significant at the $p = .001$ level. The results show a high spatial specificity of the process of deforestation regarding the considered subregions, which is illustrated by the distinct effect of the independent variables among the fitted models. The results from these subregional models also differ significantly from those presented in Table 11 for Santa Cruz as a whole. The coefficients' estimated parameters reflect the type (sign) and intensity (value) of the relation between the explanatory variable and deforestation. The Wald chi-square value reflects the relative importance of each explanatory variable compared to the other explanatory variables.

Looking at the results, one finds that colonization zones are only important for explaining deforestation levels in zones 1 and 6. In the latter, they had the opposite effect of what one would normally predict. Several zones (5 and 7) had practically no colonization zones, so the variable was not important (see Table 3). Modeling results from the pre-1989 period not presented here show that colonization zones in zones 2 and 3 were, in fact, more likely to be deforested prior to 1989. However, by the 1989 to 1994 period, the difference was no longer statistically significant. In zone 2, in particular, this may have been because large-scale mechanized agriculture became more important as a cause of deforestation compared to small-scale slash-and-burn cultivation linked with directed settlement schemes.

Even though forest concessions suffered less deforestation in Santa Cruz as a whole, that did not apply to six out of the seven zones analyzed. In four zones, there was actually greater deforestation. These were all zones close to the city of Santa Cruz. This may be due to different levels of enforcement of government policy, but it is impossible to test that hypothesis with the available information.

The only zone where protected areas provided effective protection was zone 6, which includes Amboro. In contrast, the Noel Kempff Mercado National Park, located in zone 7, apparently had no significant impact on deforestation. That was apparently due to the fact that given the park's location, limited accessibility, poor soils, and climate, there would have been little incentive for farmers to clear the forest there even without the park.

In Santa Cruz as a whole, wetter areas experienced more deforestation. However, in a number of zones, precipitation did not explain much of the difference in deforestation. In three zones, the drier areas actually had higher deforestation rates.

TABLE 12. Results of the Logistical Regression Analysis for Deforestation for the Seven Zones in the Department of Santa Cruz, 1989-94

Variable	*1*	*2*	*3*	*4*	*5*	*6*	*7*
COLO[a]	0.5936**	n.s.	n.s.	n.s.	n.s.	–0.8044***	—
	(8.389)					(12.117)	
CONC[a]	—	n.s.	1.5035**	1.1214***	0.6480**	0.9707**	–0.7427**
			(7.585)	(15.019)	(5.973)	(8.996)	(9.329)
PROT[a]	n.s.	—	—	n.s.	—	–2.7325**	—
						(7.011)	
PREC	–0.0030***	n.s.	n.s.	0.0017*	–0.0101***	–0.0020**	—
	(17.922)			(3.723)	(13.717)	(12.273)	
DIST_NF	–0.2458*	–0.0939***	–0.6131***	–0.2606***	–0.2908***	–0.3076***	–0.0842***
	(5.042)	(29.632)	(21.676)	(73.705)	(45.755)	(37.440)	(37.718)
ROAD_M	n.s.	–0.0920***	0.0297*	0.0157**	–0.0275*	n.s.	–0.0185*
		(80.061)	(4.790)	(10.424)	(4.211)		(4.525)
ROAD_S	0.0283*	n.s.	–0.0512*	–0.0348**	n.s.	0.0218*	–0.0406***
	(4.362)		(4.822)	(8.916)		(5.923)	(18.951)
TRAILS	n.s.	–0.0703***	n.s.	0.0325**	–0.0214**	0.0345**	–0.0354**
		(14.067)		(7.240)	(8.622)	(9.262)	(7.612)
DIST_SC	–0.0258***	0.0727***	n.s.	n.s.	n.s.	n.s.	n.s.
	(19.526)	(82.066)					
SOIL[b]							
II	—	n.s.	n.s.	n.s.	2.0912*	—	—
					(6.541)		
III	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	—
IV	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
V	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
VI	n.s.	n.s.	—	n.s.	n.s.	n.s.	n.s.
VII	n.s.	n.s.	n.s.	n.s	–0.7542**	n.s.	n.s.
					(7.410)		
VIII	—	—	—	—	—	n.s.	—

Note: Values in parentheses express the Wald chi-square.

a. Dichotomous (presence/absence) independent variable, absence being the reference category.

b. More than two-values categorical independent variable; the effect of each category is compared to the overall effect.

$*p = .05$. $**p = .01$. $***p = .001$.

Deforestation seems to have been highest in regions with moderate rainfall (six hundred to one thousand millimeters). Hence, in subregions with rainfall higher than that, greater deforestation occurred in drier regions, while in subregions with lower rainfall, most deforestation was in the wetter areas.

Soil quality appeared highly significant at the aggregate level. However, at the subregional level, it did not appear particularly significant, at least during the 1989 to 1994 period. That may be because each subzone was relatively more homogeneous with regard to soil quality than the department as a whole.

Even though at the aggregate Santa Cruz level, the transportation costs variables behave largely as expected, at the smaller scale the results are more diverse. In zone 1, the most deforested region with the longest settlement, distances to roads and trails no longer seems to have any significant impact on deforestation rates. Everything within that zone is basically accessible. In zones 2, 5, and 7, distance from roads and trails was generally associated with less deforestation, as hypothesized, although in a few cases, the coefficients were not statistically significant. Distance to the primary road seems to have been particularly important in zone 2, characterized by large-scale mechanized agriculture. In contrast, in zone 6, areas far away from roads and trails were subject to higher deforestation. To a lesser extent, the same holds for zone 4. It is not immediately clear why this might be the case, although it is interesting to note that during the previous period (pre-1989), deforestation had been higher in areas close to roads and trails in both those zones.

5. Conclusions

Prior to 1989, deforestation in Santa Cruz focused on the colonization zones in the wetter areas with better soils close to roads and to the city of Santa Cruz. That has tended to change, in part because the government has provided less support for colonization and economic policies have favored soybean production over rice production. Soybeans are produced more in drier areas with only moderately favorable soils. In addition, as more of the land that is close to the city of Santa Cruz, is accessible, and/or has favorable environmental conditions has become deforested, these variables have become less important in explaining which portions of the remaining forest become deforested. This may be because areas with apparently favorable characteristics that were not deforested in the initial period have unobserved characteristics that make them less likely to be deforested.

Looking across the department, one finds that the subregions that are very arid and have very poor soils have less deforestation, but within each subregion, these variables seem less important in explaining which areas farmers clear. The government and forest concession holders seem to protect forest concessions more effectively in remote regions than in those close to Santa Cruz. Having a protected area in areas where forests are under pressure has a measurable impact on conserving forests. However, creating protected areas in remote locations with poor soils has no similar impact. The relative influence on deforestation of different types of roads and trails depends in part on how long the settlement process has been going on in a subregion and the type of farmer that dominates it.

All of this implies that when one models deforestation rates at different scales, in different subregions of an area, and in different time periods, one can expect to obtain distinct results. Hopefully, future model makers will effectively exploit this additional insights this may provide.

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