Spatial Econometric Analysis and Project Evaluation:
Modeling Land Use Change in the Darién

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FOREWORD

Under the mandate of its 8th Capital Replenishment, one of the Inter-American Development Bank's fundamental objectives is to foster sustainable development in Latin America and the Caribbean by integrating social, economic, and environmental objectives in its operations. An innovative example of this commitment is the Program for the Sustainable Development of Darien Province in Panama, a $70 million operation approved in 1998. The program's goals are to promote social equity, economic growth and environmental protection in a province that has the highest incidence of poverty in the country, diverse indigenous cultures, and a rich and irreplaceable ecosystem represented by the Darien National Park, an area of such valuable biodiversity that UNESCO has declared it both a World Heritage Site and a Man and the Biosphere Reserve.

A major component of the program involves the resurfacing of the Pan American highway, which runs roughly north south through the province to a point about 70 kilometers from the Colombian border. Given the unique cultural and environmental endowments in the region, any potentially negative environmental effects of the road resurfacing had to be anticipated and mitigated, if necessary, in conformity with the Bank's environmental impact review process. Consequently, the Environment and Natural Resources Management Division of the Bank's Regional Operations Department 2, in collaboration with the Sustainable Development Department's Environment Division, commissioned a series of baseline and impact analyses, of which this analysis was a part.

The paper illustrates the use of spatial analysis techniques to predict the land use changes that would occur after the road is resurfaced and other project interventions completed. The predictions are based on a spatial econometric model relating categories of land use to geophysical and socioeconomic variables, including transportation costs and distance from markets. The results of this model are used to predict the spatially explicit effects of road resurfacing on economic activities. The methods explored in this paper offer a promising way to combine behavioral models of human activity with geographic information to realistically assess the prospective land use changes induced by development projects. We hope the paper will encourage project developers to consider similar exercises when the environmental impacts of land use alterations are of critical concern.

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INTRODUCTION

Rural development projects seek to enhance social welfare by altering the mix of economic activities in the target region. Infrastructure investments, changes in property rights regimes, and development of new rural institutions are examples of project activities that change produce and consumer incentives to improve welfare. Project elements interact with existing natural and manmade resources to determine new optimal economic activities.

With any rural economic activity, negative and positive environmental externalities are possible. Land use changes are especially likely to generate externalities. Lower prices for consumption goods may reduce local production on environmentally sensitive lands. Higher prices, or lower production and transportation costs, for products exported from the region may encourage production with negative externalities. Improved property rights provide incentives for investments with longer payoffs that may have fewer environmental costs. The magnitude of these changes depends crucially on where project investments take place, what the existing socioeconomic and geophysical characteristics are at various places and what the range of technological choice is. In short, location matters.

In the past, it has been difficult and expensive to investigate the specific geographical and environmental impacts of these investments due to the high costs of collecting and analyzing spatially explicit data. However, new developments in geographic information software, the rapidly declining costs of computational capacity, and the development of new analytical techniques are making spatially explicit, quantitative assessments of project effects more feasible.[1]

In this paper, we take advantage of this convergence of technology, data, and techniques to provide an ex-ante assessment of the consequences of a recently financed (1998) Inter-American Development Bank (IDB) rural development project in Panama's Darién province. A major element of the project is the resurfacing of the Pan American highway which runs roughly north south through the province to a point about 70 kilometers from the Colombian border. The project also includes some port infrastructure and assignment of property rights.

Given the unique cultural and environmental endowments in the region, IDB was concerned about potentially negative environmental effects of the road resurfacing. To study the potential impacts of the project and inform the project design, IDB financed a series of baseline and impact analyses, of which this analysis was a part.

The goal of this paper is illustrate the use of spatial analysis techniques to predict land use changes that would occur after the road is resurfaced and other project interventions completed. We use the basic von Thunen insights on the role of location and transportation costs to develop a spatial econometric model of land use as a function of geophysical and socioeconomic variables and estimate it using spatial data for the province. The results of this model are used to predict *spatially explicit* effects of road resurfacing on economic activities. We also examine the effects of adding a ferry from Puerto Quimba to La Palma and changing the property rights regime, other key parts of the project. We use spatial analysis techniques to simulate how the project will affect land use at every location[2] in the province.

ENVIRONMENTAL AND CULTURAL RESOURCES OF DARIÉN PROVINCE

Darién province is at the southeastern end of Panama (Figure 1). Its southern border is with Colombia and is the point where the Central American land bridge meets the South American continent. To the east is San Blas province, a narrow strip of land that runs from the peaks of the Serranía de Darién to the Caribbean. The Pacific Ocean is to the west.

The province is a region of extremely diverse ecosystems. It contains a wide range of habitats ranging from sandy beaches to palm forest swamps and lowland and upland moist tropical

[1] For a general discussion of spatial analysis and examples of its use in development projects, see Nelson and Gray.

[2] For this study the unit of analysis is a square one half km on a side.

forest. The most abundant tree species is "cuipo" *Cavanillesia platanifolia.* At higher elevations several types of interesting ecosystems, including cloud forest and the elfin forest of Cerro Pirre, are found. Wetland forest along the Chucunaque and Tuira rivers often contains pure stands of "cativo" *Prioria copaifera* (I), a commercially desirable species (http://www.cmc.org.uk/prtected_areas/data/wh/darien.html).

The Darién National Park, located in the southernmost portion of the province, is a major world environmental resource. The park has been designated both a World Heritage Site and a Biosphere reserve.

Darién province also has important cultural resources. Three indigenous groups – Emberá and Wounaan (from the Colombian Chocó) and Kuna (Houseal, MacFarland et. al. 1985) are found in the province. The Amerindians have extensive knowledge of the forest, and despite long contact with outside societies, have managed to keep some of their traditional forest cultures. The Kuna have been studied extensively (see D'Arcy and Correa-A**.** 1985); their language and behavior are in part directed by their relationships with wild animals and plants and the symbolic and magical features they represent (see Chapin 1991 and Web address http://nmnhwww.si.edu/botany/projects/centres/darien.htm#E). Three areas within the province have been set aside for indigenous groups – the Kuna de Walá, Mortí y Nurrá Indigenous Reserve in the headwaters area of the Chucunaque River, the Chocó homelands Comarca Emberá No. 1 in Cemaco District and Comarca Emberá No. 2 in Sambú District. This protection has been provided to support traditional property rights against the encroachment of immigrants, sometimes called colonists, from other parts of Panama. A key part of the project is to support the integrity of the reserves.

THE PAN AMERICAN HIGHWAY IN DARIÉN

The Pan American highway was originally intended to extend from Alaska in North America to Tierra del Fuego in South America passing directly through the province, and what is now Darién Park. Construction of the highway in the province began in the 1970s and reached Yaviza, about two thirds of the way south of the northern provincial border, in 1984 (Figure 1). The highway was not completed, with a portion in Darién province from Yaviza south, the Darién Gap, never begun. The reasons for this omission include a concern that foot and mouth disease would enter Central America from South America and the high costs of completing the stretch through rugged territory.

Since the stretch of highway to Yaviza was completed in 1984, maintenance efforts have not kept up with weather and traffic-induced damage. The road surface has deteriorated to the point that in some places the road is only passable during the dry season months of January to March. The Panamanian government asked the Inter-American Development Bank to support a sustainable development project in the province. Project elements include:

- Designation of new protected areas of various types,
- Land titling,
- Rehabilitation of the transport infrastructure; in particular, the resurfacing of the Pan American Highway in the province,
- Strengthening of institutional capacity to enforce land use and resource management administrative capability, and
- Improved access to basic services (health, education, potable water, sanitary systems, and electricity).

The possibility for negative externalities was of particular concern because of the unique cultural and environmental attributes of the Darién. The road resurfacing lowers the cost of transporting goods to and from the province. All economic activities that use inputs from or sell output to the rest of Panama become more profitable, thereby raising land values and increasing the opportunity cost of conservation. It is possible that either expansion of existing activities or new activities could have negative environmental consequences. Effective land titling, on the other hand, lowers the implicit discount rate, making profitable long-term investments that are sometimes more environmentally friendly. Designation of new protected areas, accompanied by effective enforcement, should also reduce environmental degradation.

A MODEL OF THE DETERMINANTS OF LAND USE[3]

To predict land use changes as a result of various project activities, we use a spatially explicit model of land use. A given parcel of land has a variety of characteristics that determine its inherent productive capacity. These characteristics might be vegetative (timber, productive soil), mineral, or even atmospheric (rainfall, evapotranspiration). Another set of attributes that determine profitability (and therefore land rent) is location-specific (e.g., proximity to a harbor, road, or market center).

We assume the operator (the person with effective control over the land) uses these resources to increase his or her utility. For this model development we equate utility and profit maximization. However, we relax that assumption in the empirical analysis.

The operator chooses a particular land use by comparing the net present value of the profitability of all possible land uses. If we assume that a given land use has a single marketed product, the net present value of the return to that land use, its net present rent (R_{hl}) at time T, is given by:

$$R_{hl\mathrm{T}} = \int_{t=0}^{\infty} \left(P_{hl\mathrm{T}+t}\, Q_{hl\mathrm{T}+t} - \mathbf{C}_{hl\mathrm{T}+t}\, \mathbf{X}_{hl\mathrm{T}+t}\right) e^{-i_l t}\, dt \quad (1)$$

where P is the output price, Q is the quantity of output, **C** is a vector of input costs, **X** is a vector of inputs under operator control and i_l is the location-specific discount rate, all for each land use *h* at location *l* at time *t*. The operator chooses the land use that has the highest R_{hlT} for the parcel.

The theoretical derivation, presented in an appendix, makes several restrictive assumptions to arrive at a theoretically consistent reduced form equation that includes prices of inputs and output, a vector of geophysical characteristics (**G**), parameters of the production function (***a*** and ***b***), and a location-specific discount rate, ***i***.[4]

$$\begin{aligned} R_{hlT} &= b_h \left[P_{hl} G_l \prod_k C_{khl}^{-a_{kh}} a_{kh}^{a_{kh}} \right]^{\frac{1}{b_h}} \int_{t=0}^{\infty} e^{-i_l t}\, dt \\ &= b_h \left[P_{hl} G_l \prod_k C_{khl}^{-a_{kh}} a_{kh}^{a_{kh}} \right]^{\frac{1}{b_h}} \left(\frac{1}{i_l} \right) \end{aligned} \quad (2)$$

In addition, data restrictions impose additional constraints. As discussed below, we use only cross-section information. Hence we cannot use time series variation in prices to estimate parameters. However, we do have spatial variation in prices caused by transportation costs.

Since we have no data on either location-specific or final destination prices, we proxy location-specific prices by measures of cost-of-access to different final destinations. We use location-specific price proxies with the following functional form:

$$\begin{aligned} P_{hl} &= \exp\left[g_{0l} + g_{1l} D_l \right] \\ C_{hl} &= \exp\left[d_{0l} + d_{1l} D_l \right] \end{aligned} \quad (3)$$

D_l - cost of access measure from final destination or source of input to location l.

Note that this form assumes that the price proxies for all inputs (C_{khl}) are the same. We make

[3] The static version of this model was originally developed in Chomitz and Grey and used to assess the effects of roads on land use in Belize. Nelson and Hellerstein extended the theoretical model to multiple time periods and used the approach to simulate the land use effects of complete removal of a road network in central Mexico. Other authors who have used this methodology to study determinants of land use in developing countries include Deininger and Minten. Bockstael and associates at Maryland have used a similar methodology to study urban expansion in the Washington, DC/Baltimore, Maryland corridor. See Kaimowitz and Angelsen for a review of deforestation models.

[4] The discount rate, i, is location-specific to capture differences in effectiveness of property rights. It is not uncommon for informal use rules to play a more important role in determining land use than official rules and regulations. If data on land tenure are available, they can act as a proxy for the location-specific effects of changing discount rates.

this assumption because we do not have input-specific data.[5]

For this analysis we assume there are four distinct final destinations that might be of relevance to land use choice. Some activities produce goods for home or location consumption. Two final destinations for this type of activity are proxied by the nearest village and the nearest local population center. In addition, some goods are transported out of the province. From most of the province, goods move either along the Pan American highway north or to El Real and onto a coastal sea-going vessel. We combined these two destinations, estimating the cost to the nearest. Our fourth destination was the Pacific coast town of Puerto Piña in the southwest. Puerto Piña is a viable destination only for goods produced nearby since mountains surround the town.

Substituting the price proxies and doing additional manipulations (see appendix) gives:

$$\ln R_{hlT} = h_{0h} + \sum_i h_{1ih} D_l + \sum_r h_{2hr} G_r + h_{3h} \ln i_l + u_{hl} \quad (4)$$

Parcel h will be devoted to land use k if $R_{hkT} > R_{hlT}, \forall\, l \neq k$. If the u are Weibull distributed and uncorrelated across land uses, equation (4) is equivalent to a multinomial logit model where:

$$Prob_{hl} = \frac{e^{\mathbf{V_l ?_h}}}{\sum_j e^{\mathbf{V_l ?_j}}} \qquad (5)$$

For estimation, the **V** vector consists of three sets of explanatory variables; G – site-specific geophysical variables, C – cost-of-access (D) and other socioeconomic variables, and S – spatial effects geophysical variables (discussed below).

We use the estimated ηs to generate probability predictions for each land use at every location in the province.[6] These probabilities can then be used to predict land use at each location. The predicted land use is determined by the highest probability value of the land uses. We compare the predictions to the actual land use values to assess the predictive power of the regression. A "prediction matrix" is calculated by comparing actual and predicted categories. The matrix rows show the number of locations *actually* in a given category; its columns show the number of locations *predicted* to be in a given category. Diagonal elements are correct predictions.[7]

With estimates of the ηs, we simulate changes in the socioeconomic variables brought about by the project. The project has two main elements – changes in transportation infrastructure and in property rights. To assess the effects of the proposed transportation infrastructure, we simulate the effects of road resurfacing alone and with a ferry from Puerto Quimba to La Palma. Both investments will lower transport costs from all points in the province to final consumption points (except Puerto Pina). We replace the original transport costs, based on existing infrastructure, with lower transport costs and re-estimate the predicted land use.

Changes in property rights influence the choice of land use through the effect on the discount rate. More secure property rights lower the effective discount rate for the operator of a parcel and increase the net present value of investments with longer-term payoffs. Project staff suggested that the inhabitants of the Cemaco reserve have the most effective property rights over land in the province. We simulate the expansion of this degree of control to the entire province to illustrate how improved property rights for the indigenous population might change land use.

For all alternatives, we generate transition matrices[8] and land use change maps.

[5] This assumption does not mean the effect of a change in access cost is the same for all land uses. See Greene for a theoretical explanation and Nelson and Hellerstein for an example.

[6] For example, we might find the following land use probabilities at a location in the middle of the park – forest without cuipo – 72%, forest with cuipo – 18%,
orest without cuipo – 72%, forest with cuipo – 18%,
agriculture – 3%, pasture – 6%, etc. The sum of probabilities for all nine categories is 100%.

[7] The prediction matrix is like a "confusion matrix" in the remote sensing literature that compares categories identified by a classification scheme to categories identified by ground observation (Richards 1993).

[8] A transition matrix has one state of nature (e.g., 1987 land use) along the vertical and a second state

DATA SOURCES AND DATA MANIPULATION

The principal source of data was a spatial data set prepared by the Dames and Moore Panama office as part of project preparation. The data consist of over 80 coverages[9] stored in Arc Info and Arc View file formats. Variables include land use, location of population centers by ethnic group, soil type, rainfall, elevation, and political boundaries.

Land Use

Dames and Moore derived land use data sets for 1987 and 1997 from a variety of sources, including interpretation of satellite images and ground-truthing (Table 1 and Figure 2). The original land use classification had 15 categories, but some represent areas – interior waters and populated areas – that are essentially 'no data' for the purposes of our analysis. To simplify the interpretation, we aggregated the original land uses into 9 categories (0 to 8 in Table 1). The original data were in vector coverages; we converted these to raster coverages with each pixel representing an area 500 meters on a side (0.25 sq. km.).

The data set identifies five categories of land use involving forest. In 1997, forests accounted for about three-fourths of the land area in the province, a decline of about 10 percent from 1987. Two categories – forest with and without cuipo (bosque con cuipo and bosque sin cuipo) – account for most of the forest area.[10] The principal distinguishing characteristic of the two is the presence or absence of cuipo trees. This tree resembles the African baobob in appearance. Its wood is unsuitable for most timber needs. The cuipo-dominated forest is located at lower elevations and relatively close to human activities. The non-cuipo forest is located in more remote locations and locations with higher elevation and steeper average slopes (Table 3). The third important forest category is cativo. This is the most important single species, used principally in the plywood industry. Since it often grows in pure stands it is especially susceptible to clear cut logging.

During the 1987-97 period, the largest decline in forest area was in the forest with cuipo category. Almost 20 percent of this category was lost with brush, pasture, and agriculture taking about 5 percent each (Table 2).

The Dames and Moore analysts identified about 700 square kilometers of mangrove and other wetland areas. These are located almost exclusively around the Gulf of San Miguel. There was relatively little change in this area between 1987 and 1997.

The remaining categories reflect human intervention. The largest categories are livestock pasture (ganadería) and brush (matorrales). Project staff described the brush category as the land cover following slash and burn cropping practices or where pastures were abandoned. There was a very large increase in both these categories with the brush area doubling and the livestock area increasing by more than 50 percent (Table 2). As can be seen in Figure 2, most of this increase came in the northwest part of the province, largely at the expense of the forest with cuipo category.

Agricultural area increased by almost 75 percent between 1987 and 1997, but from a relatively small base. Much of the increase took place at the edges of existing cultivation and from cuipo forests (Table 2). One exception is a large area of agricultural activity near the northernmost corner of the province.

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of nature along the horizontal (e.g., 1997 land use). A matrix cell contains the number of members common to both the first and second state. For example, if 9 square kilometers of cativo forest in 1987 were converted to pasture in 1997, the intersection of the 1987 forest column with the 1997 pasture row would be 9.

[9] A coverage is set of location-specific values for a variable. In a vector coverage, location information is given as a polygon or other vector format. In a raster coverage, location information is given in a grid of squares, sometimes called cells or pixels (short for picture element). Pixel and cell are used here synonymously with location of a parcel.

[10] It is unclear whether the presence of cuipo is primarily a function of elevation or degree of human intervention.

Table 1: Land Use Categories and Areas, 1987 and 1997.

Category (number in parentheses)	*1987*	*1997*	*Change*
	Area (sq km)		*% change*
Forest	**13,529**	**12,133**	**-10**
Bosque sin Cuipo (forest without cuipo) (0)	4,631	4,613	-0.4
Bosque con Cuipo (forest with cuipo) (1)	8,085	6,608	-18.3
Cativo (2)	246	234	-4.9
Plantaciones Forestales (plantation forest) (3)	0	5	
Bosque Intervenido (disturbed forest) (3)	568	673	18.6
Mangrove and other wetlands	**729**	**717**	**-2**
Mangle (mangrove) (4)	442	416	-5.9
Mangle Arbustivo (4)	21	27	29.9
Mangle con Alcornoque (4)	37	37	-0.2
Pantanos (freshwater wetland) (5)	229	237	3.5
Human intervention	**1,852**	**3.268**	**76**
Matorrales (brush, often after slash and burn agriculture) (6)	566	1,134	100.3
Ganadería (livestock) (7)	903	1,469	62.6
Agrícola (agriculture) (8)	383	665	73.8
Other	**147**	**30**	
Aguas Interiores	132	15	
Poblados (village)	15	15	
Total area	**16,258**	**16,148**	

Source: Calculations based on data collected by Dames and Moore.

Note: The difference in total provincial area between the two periods come from an apparent decline in area classified as interior waters between 1987 and 1997.

It is also informative to look at the spatial distribution of changes in land area. The center graph in Figure 2 shows that most of the change took place in the northern part of the province. Land use changes took place on both sides of the highway. However, the changes on the east side were located predominately in the narrow strip between the highway and the Chucunaque River, outside the Cemaco Reserve. Changes on the west side of the highway took place throughout the northwest corner of the province.

Geophysical data

Geophysical variables determine the potential productivity of different land uses at a location (see Table 3). We started with the basic data provided by Dames and Moore and then manipulated them to generate other variables for the analysis.

Precipitation

The precipitation data set provided by Dames and Moore rainfall values in 1,000 mm increments, ranging from 0 to 5,000 mm. Furthermore, the rainfall polygons are quite large, suggesting these data are not too reliable. Average rainfall was highest in the mangrove areas (3,650 mm/yr) and lowest in the forest without cuipo areas (1,840 mm/yr).

Table 2: Land Use Transitions, 1987 to 1997 (sq. km.)

1987 Land Use	1997 Land Use									
	0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**Total, 1987**
Forest without cuipo 0	**4,588**	11	1	5	1	0	9	3	7	4,624
Forest with cuipo 1	5	**6,499**	1	377	1	26	406	525	250	8,090
Forest with cativo 2	0	1	**226**	0	0	0	9	2	2	240
disturbed forest, secondary forest, forest plantations 3	0	57	0	**200**	0	0	144	133	17	552
Mangrove areas 4	0	1	0	14	**401**	2	2	4	0	423
Fresh water marshes 5	0	17	0	5	1	**197**	0	0	0	220
Scrubs or secondary growth 6	0	3	0	28	0	0	**457**	29	46	563
Pasture 7	0	15	0	28	1	0	76	**770**	8	898
Agriculture 8	0	1	0	5	0	0	29	7	**341**	382
Total, 1997	4,593	6,604	228	663	405	225	1,130	1,473	671	15,991

Note: Entries in a cell indicate the number of square kilometers that were in the row land use in 1987 and the column land use in 1997. For example, 525 sq. km. that were in forest with cuipo (1) in 1987 had been converted to pasture (7) by 1997. The entries along the diagonal are areas where land use has not changed. The totals differ from those in Table 1 because some locations were identified as missing in one period while other locations were missing in the other period.

Elevation and slope

Elevation values were derived from a radarsat raster image with pixel size of 92 meters. The average slope was calculated from the original data. Then both elevation and slope data were resampled to 500-meter cells. The highest point in the province is 1,800 meters but much of the province is close to sea level. The average elevation is 291 meters and the average slope is 6.7 degrees. However, some land use categories have very different average values. The average elevation of a forest without cuipo location is 658 meters and its average slope is 13.51 degrees. These values indicate the rugged topography where forest without cuipo grows; the reason it remains inaccessible and well-conserved.

Socioeconomic Data

The socioeconomic variables are chosen to reflect the influence of humans on land use (see Table 3). Four 0-1 dummy variables – for the national park, the Cemaco and Sambú reserves and concession areas – are included to capture variations in the degree of human control over the land use. If park protection is effective we expect to see less human intervention there than would otherwise be the case. Forty seven percent of forested pixels are in the park and a further 28 percent are in the Cemaco reserve. Only 3 percent of the pixels with human intervention were inside the park, 7 percent in the Cemaco reserve, and 5 percent in the Sambu reserve.

Darién National Park

Darién National Park was established in 1980. It is located on the southern border of the province and makes up about one third of the provincial area. UNESCO designated the park a World Heritage Site in 1981 and a biosphere reserve in 1983. With a few exceptions (such as mineral concessions that preceded the park creation), no economic activity is supposed to take place within these boundaries. However, the ability to enforce this restriction is limited by the small number of park personnel.

Concession areas

The Dames and Moore data set includes information on the two types of concession areas in the province – forest and mineral. Two mineral concessions are located in the park and the remainder are just outside the park boundaries. The forest concessions are in three groups – one near the park border, one in the middle of the province and several in the northeast corner of the province.

Table 3: Mean values for explanatory variables for the province and within each land use category, 1997.

Name	Forest without cuipo	Forest with cuipo	Forest with cativo	Disturbed forest, secondary forest, forest plantations	Mangrove areas	Fresh water marshes	Scrubs or secondary growth	Pasture	Traditional agriculture	Province	Units
ID	0	1	2	3	4	5	6	7	8		
Area	4,594	6,604	228	663	408	225	1,131	1,473	671	15,995	sq. km
Geophysical variables											
ELEV	6.58	1.79	0.72	1.12	0.36	0.43	0.89	1.21	0.80	2.91	100 meters
RAIN	1.84	2.72	3.47	3.47	3.65	3.57	3.42	3.38	2.86	2.66	meters
SLOPE	13.51	4.80	1.13	3.79	2.14	0.93	2.45	3.52	2.32	6.70	degrees
Spatial lag variables											
COLINDX	164	145	119	94	73	122	112	73	147	137.00	increases from east to west; each unit is .5 km
ROWINDX	259	202	145	148	170	206	171	131	218	207	increases from north to south; each unit is .5 km
Socioeconomic variables											
DARPARK	0.76	0.27	0.00	0.01	0.00	0.01	0.03	0.00	0.13	0.34	1- in park
CONCESSN	0.02	0.05	0.18	0.03	0.00	0.01	0.05	0.03	0.08	0.04	1- in concession
CEMACO	0.22	0.23	0.36	0.02	0.00	0.00	0.10	0.01	0.24	0.18	1- in Cemaco reserve
SAMBU	0.13	0.07	0.14	0.01	0.00	0.00	0.06	0.02	0.11	0.08	1- in Sambu reserve
COST2PTS	126.36	36.20	14.95	10.02	13.29	12.69	14.27	7.88	28.95	55.33	$/mt cost to nearest of northern border or El Real
COSTPP	255.49	241.82	231.60	223.04	219.84	229.83	220.76	223.54	214.09	239.76	$/mt cost to Puerto Pina
COSTVILL	72.57	16.30	3.41	1.18	2.09	6.49	1.29	0.56	1.85	28.03	$ cost to nearest inhabited village
COSTTWN	87.80	26.08	8.98	3.22	4.00	7.61	3.35	2.51	5.27	37.14	$/mt cost to nearest town

Source: Own calculations using Dames and Moore data set.

Cemaco and Sambu Reserves

Although three areas have been set aside for indigenous groups in the province (see above) we have included only two in the econometric estimation – the Chocó homelands Comarca Emberá No. 1 in Cemaco District and Comarca Emberá No. 2 in Sambú District. These reserves were set up in 1983. Discussions with project staff suggested that residents in these reserves had been most successful in using the reservation status to gain effective property rights. The third reserve, the Kuna de Walá, Mortí y Nurrá Indigenous Reserve in the headwaters area of the Chucunaque River, was only created in 1997.

Cost of Access Data

Ideally, we would use prices of important inputs and outputs to determine the most profitable land use at each location. These data are unavailable. However, we do have information on the cost of transporting wood, an important product of the region. We used timber as a proxy for all transported outputs.[11] In a study of logging in Brazil, Stone estimated the costs of transporting a cubic meter of wood over various land surfaces and navigable waters (Stone 1998). We calibrated these cost estimates to reflect local conditions based on information provided by project staff.

[11] Timber is similar to other agricultural products in weight and volume. It may be the case that other agricultural products are exported from the province in less than full truckload lots and hence we are underestimating the transport cost for those commodities. This possibility would need to be checked in follow up work on monitoring and evaluation.

Project staff identified several stretches of rivers in the province that are navigable by small boats. These include the Chucunaque River as far north as the Meteti area, the Tuira River as far south as Boca de Cupe and the Sambu River to Boca de Sabalo. In addition, we assumed that the gulf waters were navigable at the same cost as the rivers. We added an additional fixed cost to move goods onto or off the gulf to reflect loading costs. An important implication of these assumptions is that the cost of moving goods out of the province via a water route (river and gulf) is similar to using the Pan American highway. Where cost information was not available from Stone, we used estimates based on our best guesses and discussions with project staff.

Table 4 presents our estimates of the cost of moving a cubic meter of wood over a kilometer of various land use categories, assuming a flat surface. These costs are then adjusted to reflect the higher cost of moving over sloping ground.[12]

Table 4: Cost of traversing different land surfaces.

Land use category	*Cost per cubic meter per km ($)*
Primary road	0.10 (0.05 after resurfacing)
Secondary road	0.15
Navigable river	0.08
Bosque con Cuipo	3.00
Bosque sin Cuipo	3.00
Cativo	3.00
Bosque Intervenido	0.50
Plantaciones Forestales	0.50
Mangle	3.00
Mangle Arbustivo	3.00
Mangle con Alcornoque	3.00
Matorrales	0.50
Pantanos	3.00
Ganadería	0.20
Agrícola	0.20
Poblados	0.20

Source: (Stone 1998, discussions with project staff, and own estimates).

Figure 3 presents graphs of the minimum cost of moving a cubic meter of wood to various destinations. We include four destinations – the nearest village (COSTVILL), the nearest large town (COSTTWN), Puerto Piña on the Pacific Coast (COSTPP), and the lowest-cost option to exit the province, either north along the Pan American highway or through El Real to the Pacific Ocean (COST2PTS).

As might be expected the lowest cost points are those nearest the destinations and along roads and navigable rivers that provide easy access to those destinations. The average cost of access to different land use categories varies quite dramatically (Table 3) and is indicative of their locational rents. The average cost from a forest without cuipo pixel to the lowest cost destination outside the province is $126 because these locations are both remote and have a large slope. The average cost from a pasture pixel is only $8 because these are located on relatively flat ground in the northern part of the province near the highway.

Spatial lag variables

The variables described above are derived from data where potentially important spatial relationships exist. For example, all else equal, a location is more likely to have human intervention if the neighboring locations have human intervention. In order to correct for spatial dependence and autocorrelation (Anselin), two additional variables were included in the analysis - one each for latitude and longitude (see Table 3). The latitude grid has a value of one for the first row of pixels, two for the second row, and so on. Each unit is .5 km further away from the northernmost part of the province. The longitude grid has a value of one for the left-hand side column of pixels, two for the column to its right, and so on. Each unit is .5 km west of the previous unit.

RESULTS

Changes in access cost and the profit frontier

A principal concern about the highway resurfacing is that it will expand the areas were land use activities with negative externalities are profitable, especially timber harvesting and crop and livestock agriculture. One way to envision this effect is to think of a "profit frontier" for land use activities. This frontier is a line (or curve) that divides the province into regions

[12] The formula for the final cost was $(1 + slope^2/50)$ times land cover cost from Table 4. This formula is arbitrary. It has the desirable properties that as slope increases, cost increases more rapidly. When the slope is 10 degrees, the cost doubles.

where an activity is and is not profitable. Within the frontier it is profitable to undertake the activity. Outside the frontier, the transport cost is greater than the value at the destination.

One of the authors (Stone) collected prices of wood products processed from various tree species in August 1998 (Table 5). Mahogany is by far the most valuable species at over $400 per cubic meter in Yaviza. Cedar is worth about half as much as mahogany and pavé is worth only about $130 in Yaviza.

For most of the province, transport costs to a final destination are below $50 per cubic meter. The highest cost with existing transport infrastructure is $431 per cubic meter. However, this cost is found only in the most remote southern corner of the province (Figure 3).

Table 5: Price of wood at various locations (August 1998)

Product	*Location*	*Price ($/board ft.)*	*Equivalent Price ($/cubic meter)*[1]	*Condition*
Mahogany	Yaviza	1.00	424	Rough sawn
Cedar (cedro espinosa)	Yaviza	0.50	212	Rough sawn
Pavé (softwood)	Yaviza	0.30	127	Rough sawn
"	Meteti	0.35	148	Rough sawn
"	Panama City	0.53	225	Rough sawn
"	Panama City	0.70-75	297 – 318	Finished sawn

1. One cubic meter = 424 board feet.

For essentially the entire province, the value of mahogany is higher than the cost of transporting it out of the province. The mahogany profit frontier lies outside the province. The frontiers for cedar and pavé are also relatively remote. Regions where it is unprofitable to harvest these species are mainly near Puerto Piña (assuming that the outlets are either through the Gulf or along the highway). Hence, even without resurfacing the road or completing the ferry it is highly profitable to harvest mahogany anywhere and to harvest cedar and pavé in most locations in the province.

In other words, resurfacing the road has little effect on the profitability of extraction of high value timber. The primary effect came when the road was opened in the 1980's. The practical significance of this finding is that it is likely that the entire province has already been "high graded" or selectively cut for high value species. We do not have prices for other agricultural products of the province. It seems likely that the profit frontier would be much closer to the road.

Predictive power of the regression

We estimated the multinomial logit model (equation 5 above) using 1997 data. We have 9 land use categories (see Table 6) and the 13 explanatory variables listed in Table 3.[13] Table 6 presents the prediction matrix for the regression. The predictive power is high (70 percent of locations or more predicted correctly) for four of the nine categories – forest with and without cuipo, mangroves, and pasture. For several of the categories involving human intervention, the misclassified pixels were identified as a similar category. For example, category 6 is scrubs and secondary growth after abandoned agricultural production or pasture. Over 25 percent of these pixels were misclassified as pasture and another 8 percent were misclassified as agriculture. If all categories involving human intervention are

[13] We do not report the coefficients of the model nor their standard errors for two reasons. First, the number of coefficients equals the number of independent variables (14 including the constant) times the number of land use categories (9) for a total of 146 coefficients. Second, there is no intuitive explanation for their values. It is possible to calculate marginal effects coefficients but their values are a function of the values of the independent variables and hence vary by location. See Nelson and Hellerstein for an example of this calculation.

aggregated (3,6,7,8), the predictive power for this aggregate category is 82.3 percent.

Another source of misclassification is border effects. Pixels that lie on the border between land use categories are frequently misclassified. This can be seen most clearly in Figure 5 in combination with Figure 2. For example, in the southeast part of Figure 5, the border between the forest with cuipo and without cuipo is clearly delineated by misclassified pixels.

An additional test of the predictive power of the model is to simulate the complete removal of roads from the province and compare the results to actual land use in 1987. The Pan American highway to Yavisa was completed in 1984. If land use changes are driven primarily by ease of access, land use changes in 1987 would reflect the early stages of the effects of the road. We simulate removing roads by reestimating the cost surfaces. For pixels that include a road, the transport cost is increased to the cost of moving across the underlying land use category.

As Figure 6 indicates, simulated land use changes from "removing" the roads are similar in location to those of the actual land use changes. The change in land use brought about by removing roads is in the direction of less human intervention. In particular, most of the land in pasture in 1997 reverts to brush or forest when the roads are removed. These results give additional confidence that the model correctly estimates the effects of changes in transport costs.

COST REDUCTIONS FROM RESURFACING THE HIGHWAY AND ADDING A FERRY TO LA PALMA

A comparison of the transport costs before and after road resurfacing indicates that resurfacing the road has a relatively small effect on the cost of access to the two exterior destinations (Figure 4). The length of the road to be resurfaced is approximately 80 km within the province. We assumed that resurfacing reduces the transport cost per cubic meter from $0.10 to $0.05 per kilometer. This implies that the total saving from a point that uses the entire road for transportation is approximately $4 per cubic meter. However, we have also assumed that transport along navigable rivers to the Gulf of San Miguel is also possible. A good may exit the province either along the highway to the north or through the Gulf, depending on the least-cost routing. Hence, there are virtually no points where the cost reduction from the resurfacing will attain the $4 maximum.

Addition of the ferry crossing from La Palma to Puerto Quimba across the Gulf of San Miguel would reduce the cost of transporting goods from the southwest of La Palma north along the Pan American highway somewhat (Figure 4). However, since goods can be transported through the Gulf, the effect of the ferry on reducing costs is confined to the area around La Palma.

Table 6: Prediction matrix, 9 land use categories, 1997 data (sq. km.).

Predicted-> Actual	0	1	2	3	4	5	6	7	8	Total	Percent correct
Forest without cuipo 0	**4,209**	373	0	0	2	2	0	0	7	4,594	91.6
Forest with cuipo 1	243	**6,053**	6	31	30	38	83	66	54	6,604	91.7
Forest with cativo 2	0	149	**25**	0	15	1	24	3	11	228	10.9
disturbed forest, secondary forest, forest plantations 3	5	50	0	**26**	36	9	189	327	22	663	03.8
Mangrove areas 4	0	27	0	0	**296**	24	23	33	5	408	72.5
Fresh water marshes 5	0	62	0	0	41	**111**	10	2	0	225	49.1
Scrubs or secondary growth 6	5	216	14	18	22	3	**322**	438	95	1,131	28.5
Pasture 7	13	27	4	9	29	0	132	**1,239**	22	1,473	84.1
Agriculture 8	6	232	22	0	6	0	51	60	**295**	671	44.0
Total	4,480	7,188	71	83	475	187	836	2,165	510	15,995	

Note: Diagonal (bold) cells indicate correct predictions.

Simulated effects of infrastructure investment

To model the effects of the project, we do three simulations (in addition to the no roads simulation described above) – resurfacing the road, resurfacing the road and adding a ferry to La Palma, and expanding the land management regime of the Cemaco reserve to the entire province. This last simulation is not meant to represent an actual project element. Rather, it is included to suggest the potentially important impact on land use of effective control for particular groups.

The effects on gross land use changes are reported in Table 7, the transition matrices in Table 8, and maps of simulated land use are in Figure 7 to Figure 9. We simulate the effects of the road resurfacing and addition of the ferry by replacing the original cost variables (cost to nearest export destination, cost to nearest village, cost to nearest town, cost to Puerto Pina) with updated variables that reflect the reduced cost. Setting the 0-1 reserve location dummy variable to 1 for the whole province simulates the change in property rights.

Two caveats about the assumptions implicit in this analysis are appropriate here. First, the simulated changes in land use should be viewed as a move from an existing equilibrium to a new equilibrium or as a change that occurs *in addition to* any ongoing changes. The infrastructure investment adds economic incentives to change land use in selected locations in addition to the incentives that already exist. Second, the analysis says nothing about the how fast these changes might take place.

Table 7: Predicted changes in land use from infrastructure investments (square kilometers).

Categories	1997, actual	Predicted						
		1997 base[2]	*After road resurfacing*		*After road resurfacing and ferry*		*All Cemaco*	
Forest without cuipo 0	4,594	4,481	4,465	(-16) (-0.4%)	4,463	(-18) (-0.4%)	4,971	(490) (10.9%)
Forest with cuipo 1	6,604	7,188	7,238	(50) (0.7%)	7,246	(58) (0.8%)	9,305	(2,118) (30.4%)
Forest with cativo 2	228	70	31	(-39) (-55.7%)	26	(-44) (-62.9%)	239	(169) (241.4%)
Disturbed forest, secondary forest, forest plantations 3	663	84	199	(115) (136.9%)	199	(115) (136.9%)	0	(-84) (100%)
Mangrove areas 4	408	475	471	(-4) (-0.8%)	468	(-7) (-1.5%)	0	(-475) (100%)
Fresh water marshes 5	225	187	187	(0) (0%)	187	(0) (-0.0%)	0	(-187) (100%)
Scrubs or secondary growth 6	1,131	835	362	(-473) (-56.6%)	337	(-498) (-59.6%)	330	(-506) (-60.6%)
Pasture 7	1,473	2,166	2,624	(458) (21.1%)	2,679	(513) (23.7%)	911	(-1,255) (-57.9%)
Agriculture 8	671	510	419	(-91) (-17.8%)	337	(-173) (-33.9%)	239	(-271) (-53.1%)
Total	15,995	15,995	15,995		15,995		15,995	

Note: Numbers in parentheses are changes from, and percentages of, 1997 predicted area. The current areas (the second column) in this table are somewhat smaller than in Table 1 because only areas used in the analysis are included here. Some areas were omitted because of missing data for one or more variables.

1. The values in this column are the 1997 areas.
2. The values in this column are logit model predictions for 1997.

Resufacing the Pan American Highway

As expected, most of the land use change occurs along the road, in the northern two-thirds of the province (Figure 7). Resurfacing the highway has little effect on the forest without cuipo areas, especially in the south and southeast. Disturbed forest area (category 3) more than doubles with most of the increase coming at the expense of scrub.

The two most significant changes are to cativo forest and pasture. The cativo forest area declines dramatically, from 70 sq. km to 31 sq. km. This area is converted into cuipo forests and pasture. This result requires qualification. The predictive power of the model for cativo forest is not high. The actual area in 1997 was 228 square km but the predicted area before project investments was only 70 km. One explanation for this difference is that something has slowed the cutting of cativo forests in the past. If so, the losses from arising from the transportation investments might also be less. Another explanation is that the cativo forest area is not in equilibrium as the model assumes. Then we might expect more rapid loss of cativo forest. Given the economic importance of cativo, this result deserves further investigation.

Area devoted to pasture increases by almost 500 square kilometers, much of it near the road. That increase comes primarily from areas that are currently in scrub (360 sq. km.) but other land use categories also are converted to pasture. Interestingly, the model predicts that the agricultural land use declines by 91 sq. km. with about half that decline moving into pasture and scrub.

Table 8: Transition Matrices for Land Use Simulations, 1997 (square km)

Simulated Land Use Categories	**Base Land Use Categories**									
Road Resurfacing										
	0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**Total**
Forest without cuipo 0	4,465	0	0	0	0	0	0	0	0	4,465
Forest with cuipo 1	15	7,129	28	1	0	1	25	0	40	7,238
Forest with cativo 2	0	0	31	0	0	0	0	0	0	31
disturbed forest, secondary forest, forest plantations 3	0	32	0	56	0	1	103	0	7	199
Mangrove areas 4	0	2	0	0	451	4	13	1	1	471
Fresh water marshes 5	0	4	0	0	1	181	1	0	0	187
Scrub 6	0	3	4	0	0	1	335	0	20	362
Pasture 7	1	18	5	28	23	0	360	2,165	25	2,624
Agriculture 8	0	0	2	0	0	0	0	0	417	419
Total	4,481	7,188	70	84	475	187	835	2,166	510	15,995
Road Resurfacing and Ferry										
	0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**Total**
Forest without cuipo 0	4,463	0	0	0	0	0	0	0	1	4,463
Forest with cuipo 1	18	7,126	28	1	0	1	28	0	45	7,246
Forest with cativo 2	0	0	26	0	0	0	0	0	0	26
disturbed forest, secondary forest, forest plantations 3	0	33	0	55	0	1	103	0	7	199
Mangrove areas 4	0	2	0	0	447	4	12	1	2	468
Fresh water marshes 5	0	4	0	0	1	181	1	0	0	187
Scrub 6	0	3	4	0	0	1	311	0	20	337
Pasture 7	1	20	11	28	27	0	381	2,165	47	2,679
Agriculture 8	0	0	2	0	0	0	0	0	390	391
Total	4,481	7,188	70	84	475	187	835	2,166	510	15,995
All Area in Cemaco Reservation										
	0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**Total**
Forest without cuipo 0	4,481	474	0	1	0	0	0	12	4	4,971
Forest with cuipo 1	0	6,706	0	81	343	186	741	1,002	248	9,305
Forest with cativo 2	0	8	70	0	93	1	28	12	26	239
disturbed forest, secondary forest, forest plantations 3	0	0	0	0	0	0	0	0	0	0
Mangrove areas 4	0	0	0	0	0	0	0	0	0	0
Fresh water marshes 5	0	0	0	0	0	0	0	0	0	0
Scrub 6	0	0	0	2	25	0	66	236	0	330
Pasture 7	0	0	0	0	9	0	0	902	0	911
Agriculture 8	0	0	0	0	5	0	1	2	232	239
Total	4,481	7,188	70	84	475	187	835	2,166	510	15,995

Note: Entries in a cell indicate the number of square kilometers with column land use in 1997 and row land use in the simulation. For example, if the entire province is assumed to have the same land management as the Cemaco reserve, 1,002 sq. km. of land moves from pasture to forest with cuipo. The entries along the diagonal are areas where land use does not change.

Resurfacing the Pan American Highway and adding a Ferry to La Palma

Including the ferry and resurfacing the highway results in some additional land use change in the ferry area and around La Palma. As before, forest with cuipo changes little. Even more cativo forest is lost, as much of the remaining stands near La Palma are converted to cuipo forest or pasture. We suspect that this outcome arises because the pasture area expands substantially in the Rio Sambu valley, at the expense of cativo forest, brush, and agriculture.

Extending the Cemaco Reserve to the Province

It is obvious from a land use map that land use in the Cemaco reserve already differs from the rest of the province. Project staff also report that the inhabitants have been able to use the reserve status to keep colonists from the land. For hypothetical purposes, we tested the effect of stronger property rights and indigenous land use practices. The purpose of this simulation is to see what effect an equivalent level of protection throughout the entire province would have on land use. In essence, we are assuming the same level of effective control over land and the same utility function derived from land use for the entire province that currently exists in the reserve.

The effects on land use are striking (Figure 9). All kinds of land use involving human intervention are reduced. Cativo forest area almost triples. Cuipo forest area increases by over 2,000 sq. km. with that area coming from pasture, scrub and agriculture. Clearly, cultural land use ethics as well as effective property rights make a difference in land use in Daríen province. More research is needed distinguish between the two.

CONCLUSIONS AND CAVEATS

This paper has demonstrated some of the potential of spatial analysis – combining spatial data, geographic information systems and econometric techniques – in this case, to estimate land use changes for project analysis. While the integration of these techniques is still an imperfect art, the results indicate the potentially important role in determining *ex-ante* effects of project interventions with spatial components. In cases where spatial data exists, the marginal costs of using this data to predict economic behavior is minimal and its potential to inform project design quite large.

In the case of the Darien, the results of this analysis suggest that, by itself, the road resurfacing will have relatively little effect on overall deforestation, especially in the national park. And even outside the park, the without-cuipo areas will not decline much. This land use category is remote, at high elevations and with steep slopes. However, cativo forests could be dramatically reduced, and pasture areas will expand substantially. The land use change areas are concentrated in the northern two-thirds of the province about equally on either side of the highway, outside the Cemaco reserve. The addition of the ferry brings more loss of cativo forest and more expansion of pasture areas, especially in the Sambu River valley, southwest of La Palma. These results suggest specific geographic areas for project monitoring and enforcement efforts.

The results also indicate that resurfacing the road does not extend the area of economic accessibility for high value timber extraction. The primary effect of the road on timber extraction came when it was completed in the 1980s. The practical significance of this finding is that it is likely that the entire province has been "high graded" or selectively cut for high value species. It is possible that the profit frontier for lower-value agricultural crops has been expanded but we do not have enough specific data on production or prices to tell. There is likely to be large complementarities between selective (expensive) on the ground monitoring and spatial analysis. More research in this area is needed.

Cultural land use practices, combined with effective property rights extended in our hypothetical example, clearly make a difference in the resulting landscape. The inhabitants of the Cemaco reserve use their land resources differently than those on the other side of the Chucunaque River. We cannot say how much of this land use choice is due to the property rights regime per se rather than a different ethic about land use. Extending this type of control to other parts of the province could mean slower conversion of forest areas and less human-induced land use change.

The model does not address directly non-project economic incentives to convert land from forest to other activities such as macroeconomic policy changes, speculation in land value or rent-seeking; and "micro" environmental changes the project might bring about. For example, if logging takes place one or two trees at a time (high-grading) and does not change the gross structure of the forest, remotely sensed data will not pick up these changes. In order to capture these effects it is necessary to combine remotely sensed data of various kinds with on-the-ground surveys.

As with any new analytical approach there are many potential shortcomings that have not been completely addressed. We have discussed some of these throughout this document and others could be added. The key advantages of this approach are its ability to utilize spatial data to make quantitative assessments that are location specific. When time and resources are scarce, this type of analysis can be of great value in designing projects that allocate these resources to areas where they will have the largest economic returns. They can also provide some assurance of likely environmental impacts of project interventions and provide a basis for incorporating strategic and cost-effective mitigation measures.

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THEORETICAL APPENDIX

We assume that a Cobb-Douglas relationship governs all production technologies.

$$Q_h = G_l \prod_k X^{a_k} \quad 0 < a_k < 1; 0 < \sum_k a_k < 1 \tag{6}$$

$$G_l = \left(\prod_{s=1}^{S} G_s^{f_s} \right)$$ – a multiplicative combination of location-specific geophysical features that affect land use.

Let $b = 1 - \sum_k a_k$

The indirect net present value function is[14]:

$$R_{hlT} = \int_{t=0}^{\infty} \left(b_h \left[P_{hlT+t} G_l \prod_k C_{khlT+t}^{-a_{kh}} a_{kh}^{a_{kh}} \right]^{\frac{1}{b_h}} \right) e^{-i_l t} dt \tag{7}$$

Because we have no time-series data on land use, we have no time variability in prices. Then (7) can be rewritten as:

$$\begin{aligned} R_{hlT} &= b_h \left[P_{hl} G_l \prod_k C_{khl}^{-a_{kh}} a_{kh}^{a_{kh}} \right]^{\frac{1}{b_h}} \int_{t=0}^{\infty} e^{-i_l t} dt \\ &= b_h \left[P_{hl} G_l \prod_k C_{khl}^{-a_{kh}} a_{kh}^{a_{kh}} \right]^{\frac{1}{b_h}} \left(\frac{1}{i_l} \right) \end{aligned} \tag{8}$$

Taking the log of (7) gives:

$$\ln R_{hlT} = \ln b_h + \frac{1}{b_h} \left[\ln P_{hl} + \ln G + \sum_k \left(-a_{kh} \ln C_{khl} + a_{kh} \ln a_{kh} \right) \right] - \ln i_l \tag{9}$$

Since we have no data on either location-specific or final destination prices, we proxy prices by measures of cost-of-access to several final destinations. We assume that location-specific price proxies take the following functional form:

$$\begin{aligned} P_{hl} &= \exp\left[g_{0l} + g_{1l} D_l \right] \\ C_{hl} &= \exp\left[d_{0l} + d_{1l} D_l \right] \end{aligned} \tag{10}$$

D_l - cost of access measure from final destination (or source of input) to location l.

Note that this form assumes that the price proxies for all inputs (C_{khl}) are the same. We make this assumption because we do not have input-specific data.

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[14] See Beattie, Bruce R. and C. Robert Taylor. The Economics of Production. Malabar: Krieger Publishing Company, 1993, page 248.

Substituting the price proxies into (9) and performing some additional manipulations yields:

$$
\begin{aligned}
\ln R_{hlT} &= h_{0h} + \sum_i h_{1ih} D_l + \sum_r h_{2hr} G_r + h_{3h} \ln i_l + u_{hl} \\
h_{0h} &\equiv \ln b_h + \frac{g_{0l}}{b_h} + \frac{1}{b_h}(d_{0l})(b_h - 1) + \frac{1}{b_h} \sum_k (a_{kh} \ln a_{kh}) \\
h_{1ih} &\equiv \frac{1}{b_h}(g_l + (d_{ll})(b_h - 1)) \\
h_{2h} &\equiv \frac{1}{b_h} h_r \\
h_{3h} &\equiv -1
\end{aligned}
\tag{11}
$$

We have the following hypotheses about signs of the structural coefficients:

$0 < a_k < 1; \sum_k a_k < 1; \left(b = 1 - \sum_k a_k \right)$; from production function

$g_h < 0$; Location-specific output price declines with distance to final destination.

$d_h > 0$; Location-specific input price increases with distance from input source.

These hypotheses imply η_0 and the η_1 vector are negative, η_2 to be positive for G ordered so that an increase in G increases output per unit of land, and η_3 to be negative (and equal to negative 1). Parcel h will be devoted to land use k if $R_{hkT} > R_{hlT}, \forall\, l \neq k$. If the u are Weibull distributed and uncorrelated across land uses, then (11) is equivalent to a multinomial logit model where:

$$
Prob_{hl} = \frac{e^{\mathrm{Vi?\,h}}}{\sum_j e^{\mathrm{Vi?\,j}}}
\tag{12}
$$

Figure 1: Darién province overview.

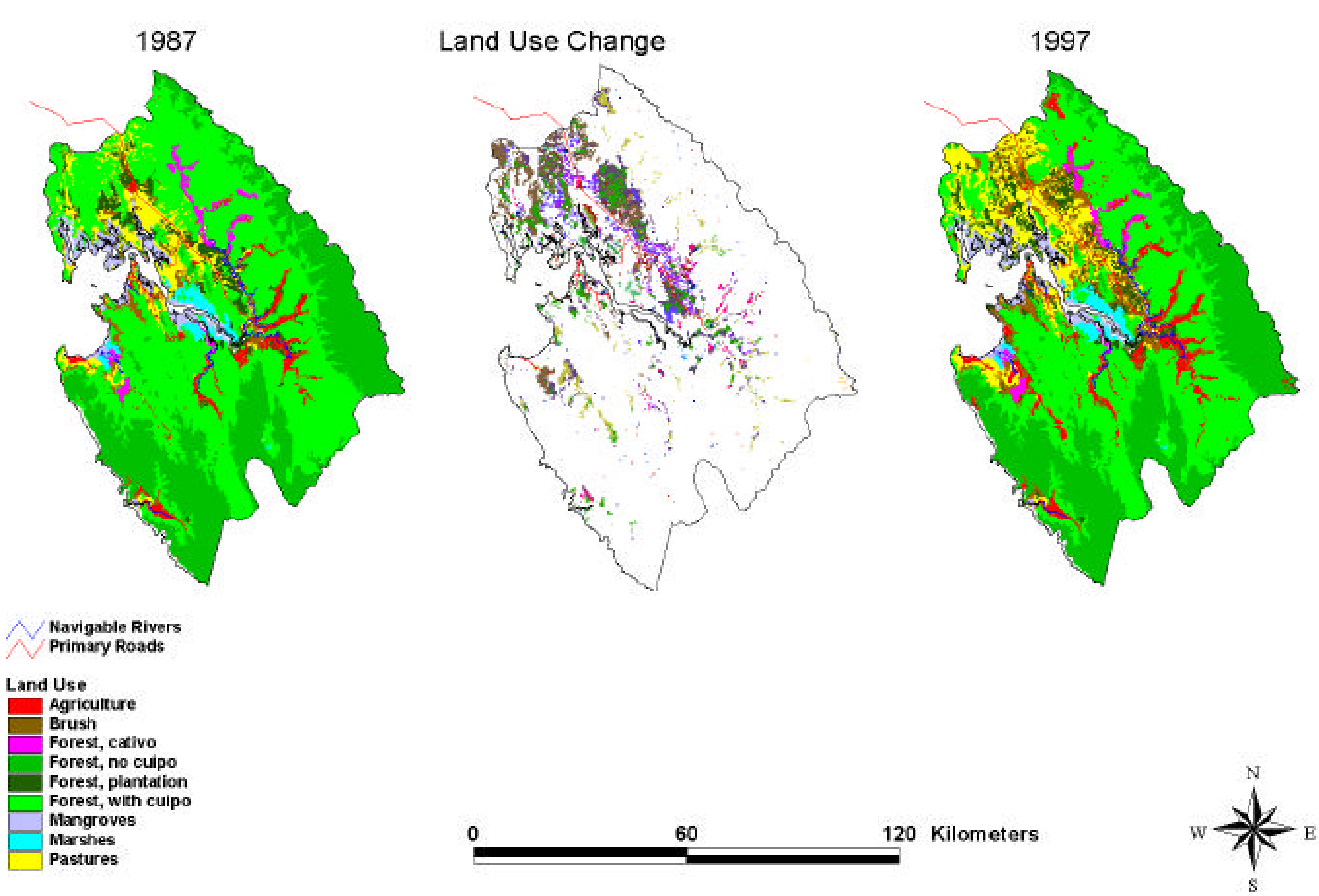

Figure 2: Darién Province Land Use, 1987 and 1997.

Note: The land use legend applies to the 1987 and 1997 figures. The colors in the center figure indicate where land use change has taken place.

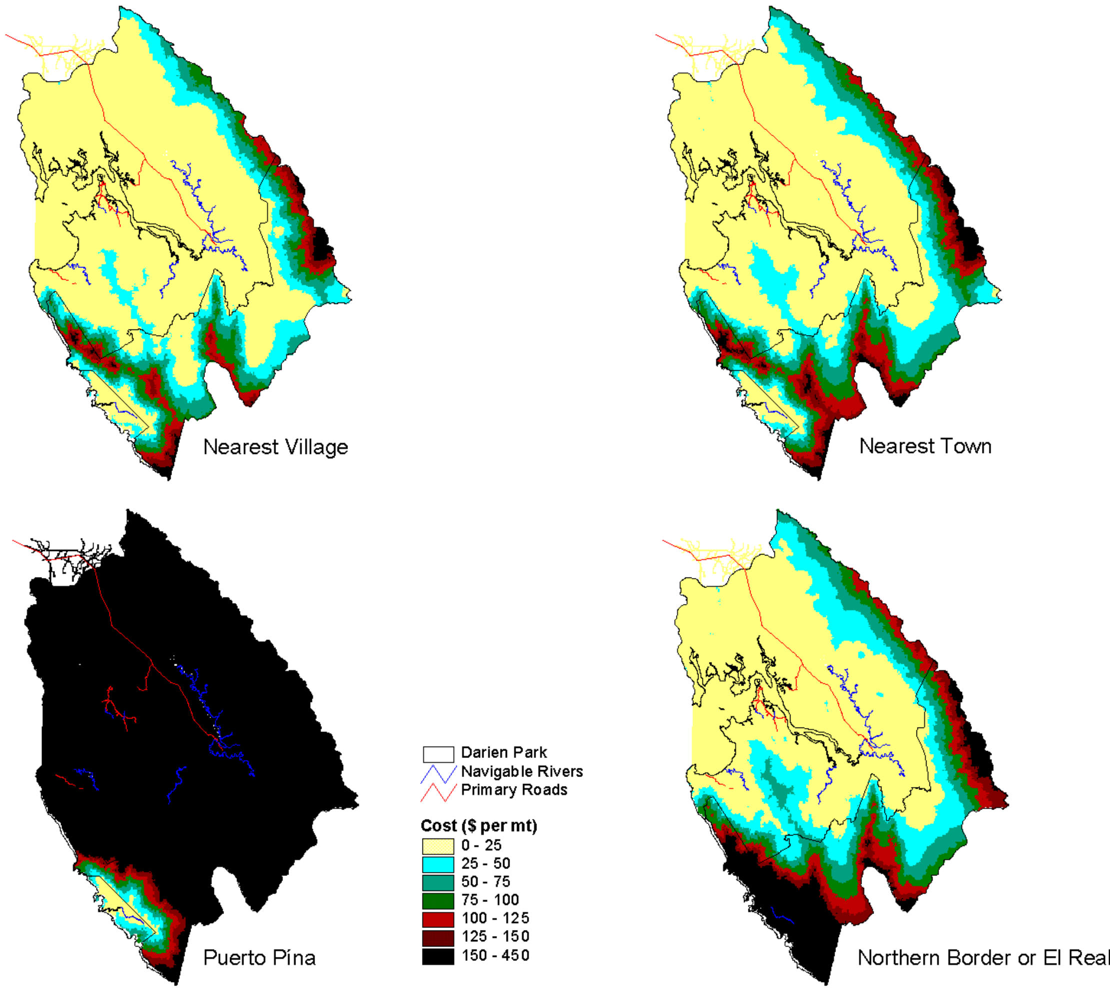

Figure 3: Minimum Cost to Nearest Destinations.

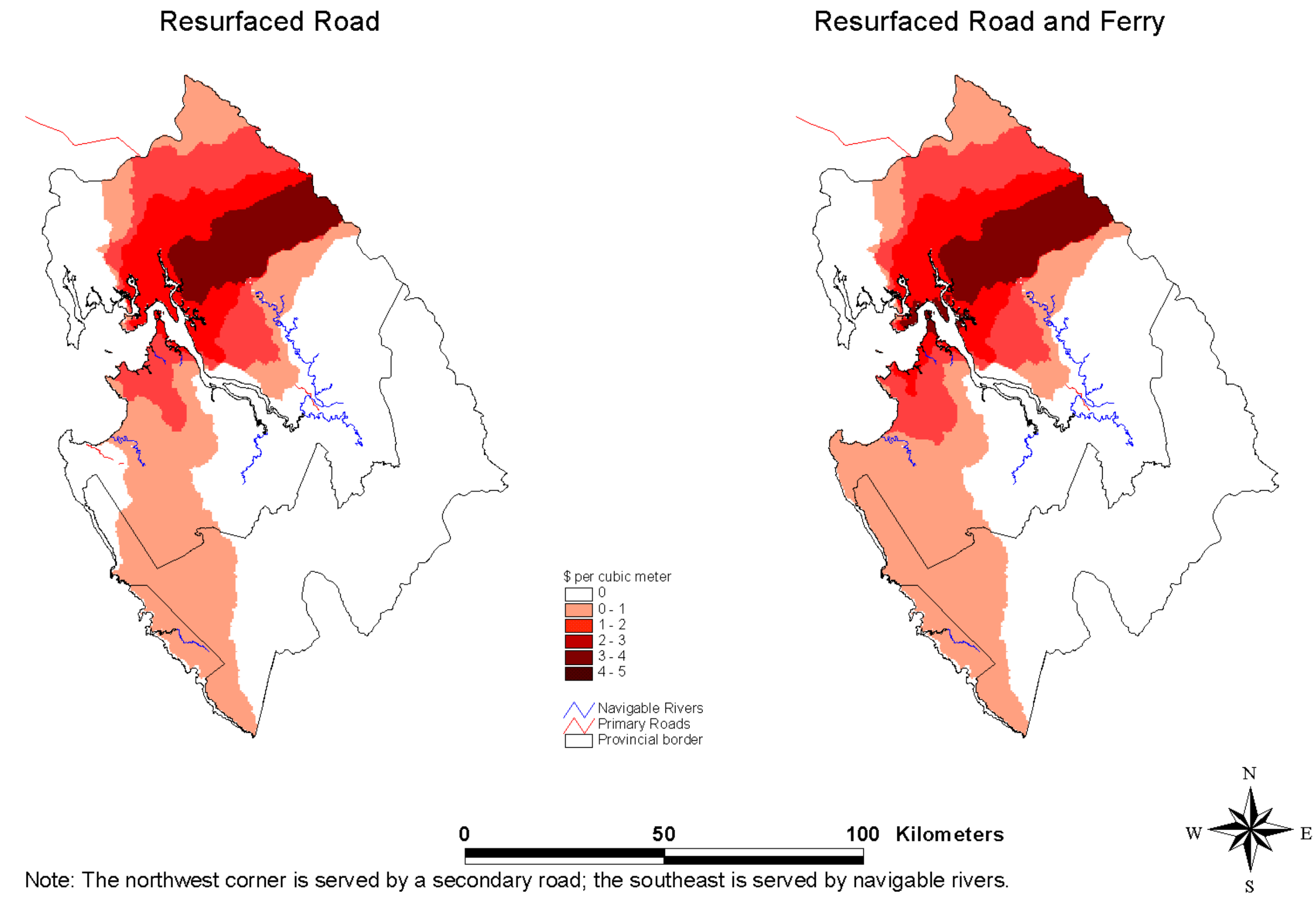

Figure 4: Reduction in transport cost to lowest export cost destination with road resurfacing and ferry.

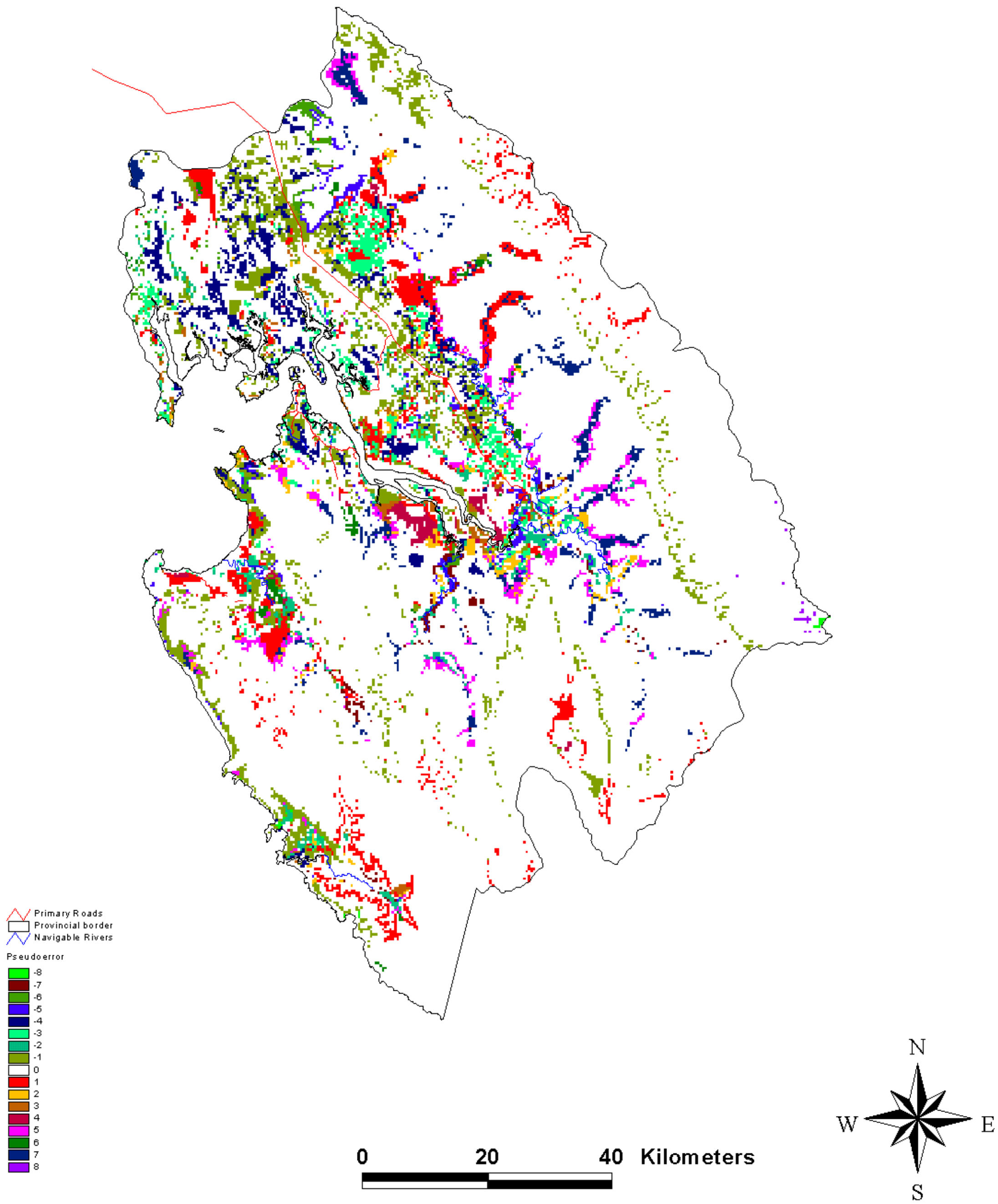

Figure 5: Spatial distribution of pseudo errors in land use prediction.

Note: The numeric value at a location is the number of the true category minus the predicted category number at that location. If predicted and actual categories are the same the location value is 0 and the color is white.

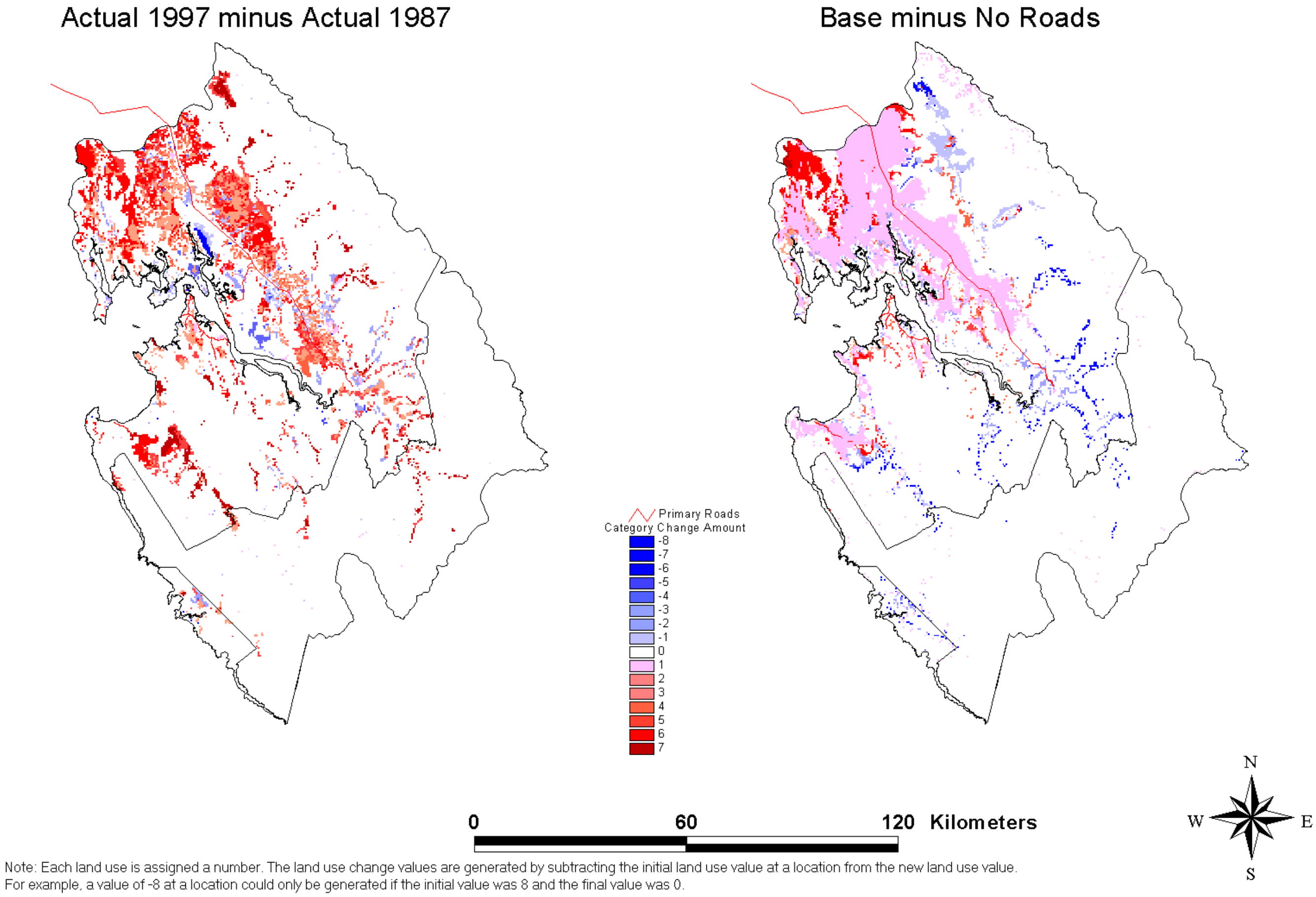

Figure 6: Land use change: 1987 to 1997 and 1997 current to simulated no roads.

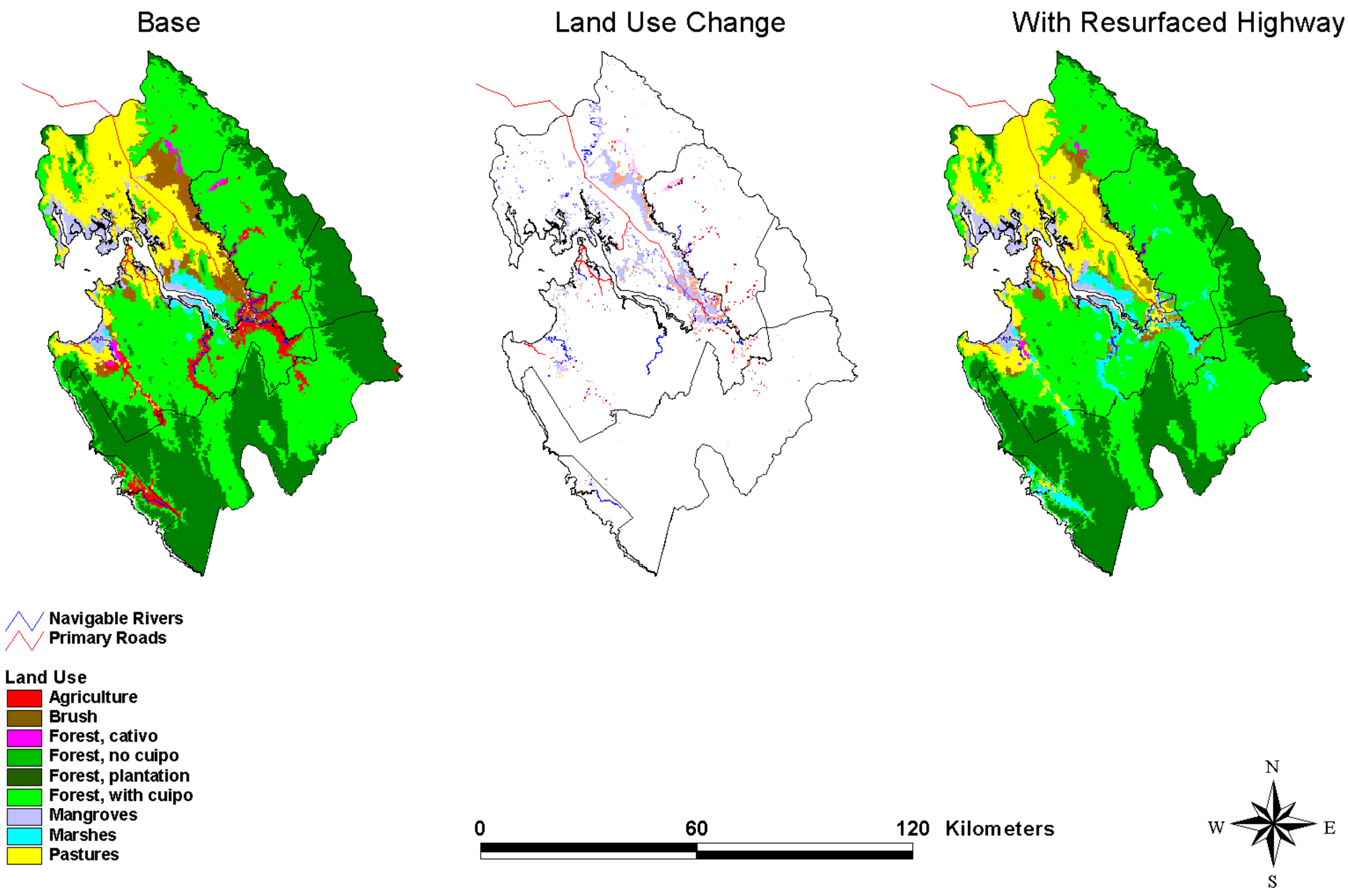

Figure 7: Land use change with road resurfacing.

Note: See Figure 6 for explanation of colors in land use change map.

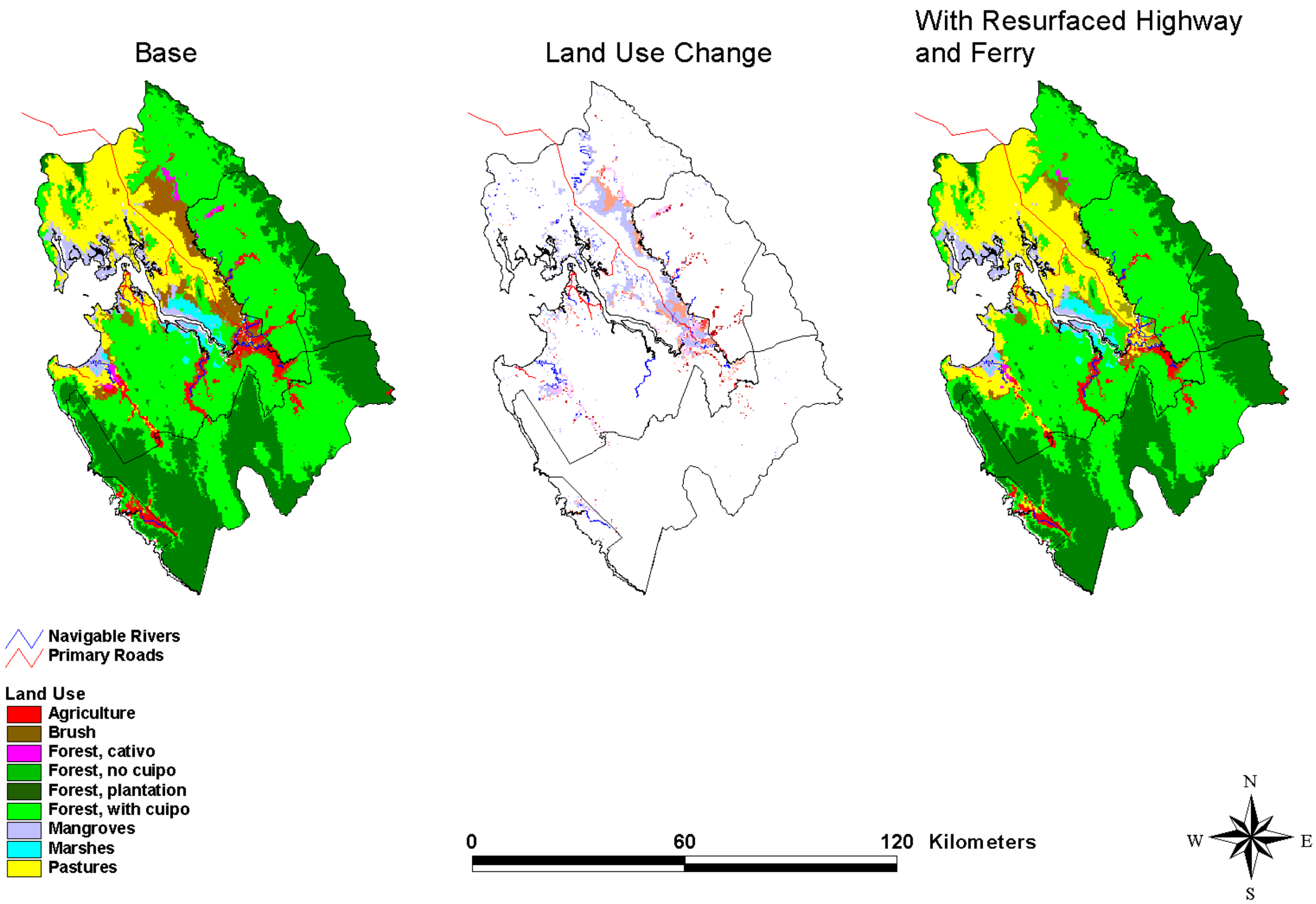

Figure 8: Land use change with road resurfacing and ferry.

Note: See Figure 6 for explanation of colors in land use change map.

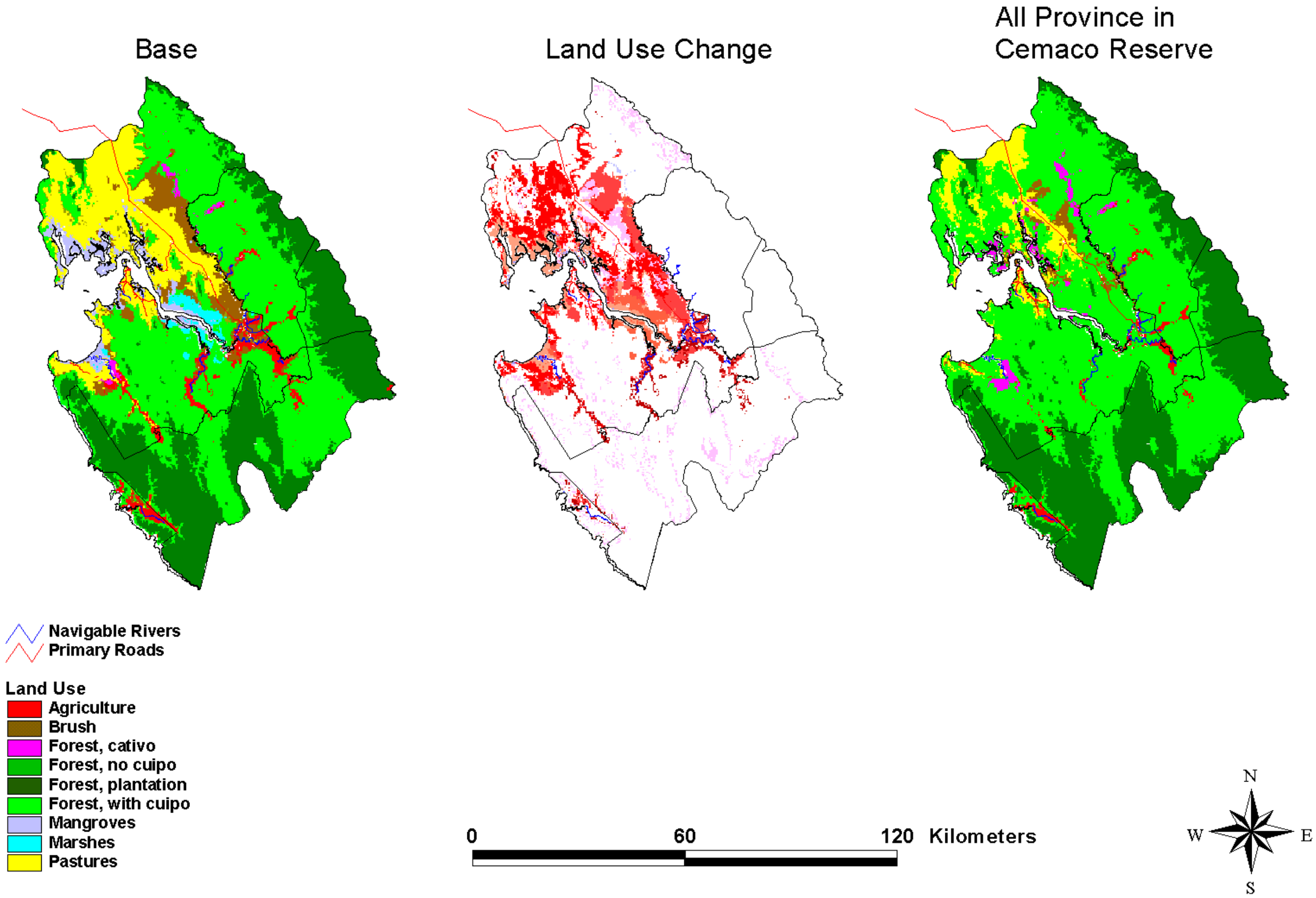

Figure 9: Land use change with all province in Cemaco reserve.

Note: See Figure 6 for explanation of colors in land use change map.