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POLICY RESEARCH WORKING PAPER 1444

Roads, Lands, Markets, and Deforestation

A Spatial Model of Land Use in Belize

Kenneth M. Chomitz
David A. Gray

Will intensifying the road network around market areas produce greater economic returns and less environmental damage than extending the road network into new areas?

The World Bank
Policy Research Department
Environment, Infrastructure, and Agriculture Division
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Summary findings

Rural roads promote economic development but also facilitate deforestation. To explore the tradeoffs between development and environmental damage posed by road building, Chomitz and Gray develop and estimate a spatially explicit model of land use. This model takes into account location and land characteristics and predicts land use at each point on the landscape.

They find that:

- Market access and distance to roads strongly affect the probability of agricultural use, especially for commercial agriculture.
- High slopes, poor drainage, and low soil fertility discourage both commercial and semi-subsistence agriculture.
- Semi-subsistence agriculture is especially sensitive to soil acidity and lack of nitrogen (confirming anthropological findings that subsistence farmers are shrewd judges of soil).

Spatially explicit models are analytically powerful because they exploit rich spatial variation in causal variables, including the precise siting of roads. They are useful for policy because they can pinpoint threats to particular critical habitats and watersheds.

This model is a descendant of the venerable von Thünen model. It assumes that land will tend to be devoted to its highest-value use, taking into account tenure and other constraints. The value of a plot for a particular use depends on the land's physical productivity for that use and the farmgate prices of relevant inputs and outputs. A reduced-form, multinomial logit specification of this model calculates implicit values of land in alternative uses as a function of land location and characteristics. The resulting equations can then be used for prediction or analysis.

The model was applied to cross-sectional data for 1989–92 for Belize, a forested country currently experiencing rapid expansion of both subsistence and commercial agriculture. A geographic information system was used to manage the spatial data and extract variables based on a three kilometer sample grid.

Three land uses were distinguished: *"natural" vegetation*, comprising forests, woodlands, wetlands, and savanna; *semi-subsistence agriculture*, comprising traditional *milpa* (slash-and-burn) cultivation and other nonmechanized cultivation of annual crops; and *commercial agriculture*, consisting mainly of sugarcane, pasture, citrus, and mechanized production of corn and kidney beans.

Two dimensions of distance to market were distinguished: the distance from each sample point to the road, and on-road travel time to the nearest town. Data on a wide variety of land and soil characteristics were also used.

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ROADS, LAND, MARKETS AND DEFORESTATION
A SPATIAL MODEL OF LAND USE IN BELIZE

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1.0 Introduction

The loss of tropical forests is a major environmental concern, because it threatens biodiversity, contributes to global warming, and has local effects on erosion, flooding and possibly climate. Considerable attention has been devoted to deforestation, and progress has been made in understanding its causes. But the relative impact of different causes, and the manner in which they interact, are poorly understood. In general, our understanding of the quantitative dimensions of deforestation processes remains extremely weak.

This is especially true for a key policy issue: road-building. Roads are closely associated with deforestation in many parts of the tropical world. However, construction of rural roads has traditionally been one of the most important tools for economic development, a tool which moreover tends to favor the rural poor. It is therefore important to quantify the impact of road-building on both deforestation and development in order to assess the severity of the trade-off between environmental preservation and economic growth.

Do all forest roads cause equally severe deforestation? Whom do these roads benefit? *A priori*, we might expect deforestation to be less where population densities are low, where soils are unsuitable for cultivation, and where markets are distant. If indeed road impacts are modulated by local conditions, then it may be possible to site roads so as to spur development while minimizing induced deforestation. In particular there may be strong implications for choices between extensification vs. intensification of the road network.

In order to explore the issue of road impacts, this paper develops and estimates a spatially explicit model of land use -- one that takes location and land characteristics into account, and predicts land use at each point on the landscape. Spatially explicit models are apt for two reasons. First, they exploit rich spatial variation in causal variables -- variation which is obscured in aggregative data (e.g. district-level means). Second, location matters. In general, we are interested not just in the areal extent of deforestation, but the degree to which it affects critical habitats and watersheds.

The model presented here utilizes spatially disaggregate data, controls for a wide variety of land and soil characteristics, employs multiple land use categories, and is embedded in an economic framework. The framework, derived from von Thünen's famous model, can be extended to explore the impacts of changes in commodity prices.

The model is estimated on data describing Belize in 1989. Still mostly forested, Belize is of great conservation interest because of its rich biodiversity and because of its relatively large tracts of contiguous forest. Despite its small size, Belize exhibits a diverse array of deforestation processes, including encroachment by swidden agriculturalists, and forest conversion to pasture, sugar, citrus, and large mechanized farms. Belize also enjoys superb documentation of land use and land characteristics, facilitating this kind of study.

The plan of the paper is as follows. We first summarize the principal policy issues and existing analyses. A nontechnical presentation of our land use model follows. (Econometrically oriented readers are referred to Appendices A and B.) Next, we discuss the relevance of Belize to the issues, and review the main features of land use there. The results of model estimation are then presented, and implications discussed. The paper concludes with a summary and discussion of next steps.

2.0 Deforestation, roads, and land use: issues and analyses

The principal purpose of this paper is to examine the impact of roads on deforestation and land use. Qualitatively, the impacts are clear. New roads offer market access for timber and for agricultural products from previously remote areas. Roads also decrease the cost of migration, access, and land clearing for subsistence farmers. In sum, road construction into forested areas unambiguously increases the incentives to log those territories or convert them to other uses.

But much hinges on the quantitative magnitude of those incentives, which we hypothesize to vary systematically over the landscape. Consider the following issues in regional and environmental planning:

Road extensification vs. intensification: Schneider (1994) and others have suggested that road-building should be intensive rather than extensive. That is, road development should stress the creation of dense road networks around market centers rather than the extension of roads into low-population density areas with good soils. While this seems to be a reasonable proposition, we lack information about the relative environmental costs and development benefits of the two strategies. Is road intensification a "win-win" strategy -- that is, does it boost output and reduce environmental damage compared to an extensification strategy? What are its distributional implications? . The significance of these questions is underlined by the rapid expansion of the road network in the tropical world. Over the 1980's, Brazil's paved road network grew from 87000 to 161,500 kilometers, and Indonesia's from 56,500 to 116,500 kilometers (World Bank, 1994). In sub-Saharan Africa, a recent review concluded that "the present rural road network ... needs to be increased up to tenfold if the full agricultural potential of the region is to be realized." (Riverson *et al.*, 1991).

Environmental impacts assessment of forest and mining concessions. According to some (Kummer and Turner, 1994; Bruce and Cabarle, 1993), logging's indirect impact on deforestation may be greater than the direct impacts of timber removal and collateral damage to standing stock. Further damage results as logging roads and operations facilitate access by follow-on settlers, who convert the logged-over forest to pasture, permanent crops, or shifting cultivation. Hence plans for the sustainable management of forest concessions need to go beyond purely silvicultural considerations. Predictive models of follow-on settlement could be employed in environmental impact assessments of proposed logging concessions, and of mining concessions which entail road-building.

Conservation planning: It is expensive to set up and maintain protected areas. Conservation planners have long recognized the need for an index of the threat of conversion as an aid to prioritizing candidate areas for protection. Such indices have been constructed as *ad hoc* functions of population density, prior conversion, and so on. Without behavioral grounding, these indices may however not be very accurate. Past deforestation rates, for instance, may be poor predictors of current rates if prices or policies have changed. Cross-sectional variation in population densities usually reflects differences in soil quality, and may bear no relation to incentives for deforestation. Much more desirable would be a methodology which measures deforestation incentives in economic terms. This could be used to calculate the opportunity cost of conservation programs, and could inform the design of conservation policies which seek to alter these incentives.

In sum, quantitative models of land use and land use change could be used for a variety of environmental planning purposes. But to be useful, quantitative studies must meet several criteria. First, they must use spatially disaggregate data. They must incorporate a wide range of land-use determinants, but recognize that population distribution, road placement, and land use change are jointly determined. Finally, they must be based on an economic framework.

No existing study for developing countries meets all of these criteria[1]. *Liu et al.* (1993) present a spatially detailed description of deforestation in the Philippines. They partition the landscape into 17 classes, based on distance from the existing road network in 1941, and show that there is a strong inverse relation between distance and proportion of forest lost over the period 1934-1988, up to a distance of 16.5 miles; from 16.5 to 25 miles, the deforestation rate was constant. This suggestive bivariate relationship, however, may arguably reflect the action of other variables. For instance, if roads were first built in areas with the most fertile soils, or if road density were higher near emerging cities, then the results may reflect the effect of soil quality and market proximity rather than the true impact of roads.

Reis and Margulis (1991) estimate a multivariate regression model of deforestation using county-level cross-sectional data from the Brazilian Amazon. The log ratio of deforested to forested

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[1] For a comprehensive survey of deforestation models, see Lambin (1994).

areas is regressed on population density, cattle density, crop area, logging activity, road density, and distance to the state capital. Road density is found to be highly significant; the coefficient on distance to the state capital is not significantly different from zero. The equation is hard to interpret, though, because most of the explanatory variables are in fact jointly determined with deforestation. That is, we would expect land conversion processes to simultaneously result in deforestation, intensification of the road network, and expansion of cropland and pasture.

An alternative modeling strategy emphasizes prices as the fundamental drivers of land use change. Multivariate regression models in this vein include Panayotou and Sungsuwan (1989) for forest area in Thailand and Barbier *et al.* (1993) for cultivated area in Mexico. Both studies use state-level panel data. Explanatory data in both include agricultural prices, provincial income or income per capita, population or population density, road density. Panayotou and Sungsuwan find that the elasticity of forest cover with respect to road density is just -0.11. Since roads affect prices, however, we would expect that some road impacts are captured in the agricultural and timber price variables, which are found to be important. By construction, however, this model will attribute to prices any road impacts which operate via changes in agricultural or timber prices; the latter is found to be quite important. The Thailand study also finds that the elasticity of forest cover with respect to distance from Bangkok is .70. Barbier *et al.*, in contrast, find that increased road density is associated with decreased cultivation area (they are not able to directly measure forest cover). Here road density may be capturing some aspects of urbanization, rather than changes in farmgate prices - an example underlining the need for highly disaggregate geographic information. Once again, virtually all the explanatory variables in both studies are arguably endogenous.

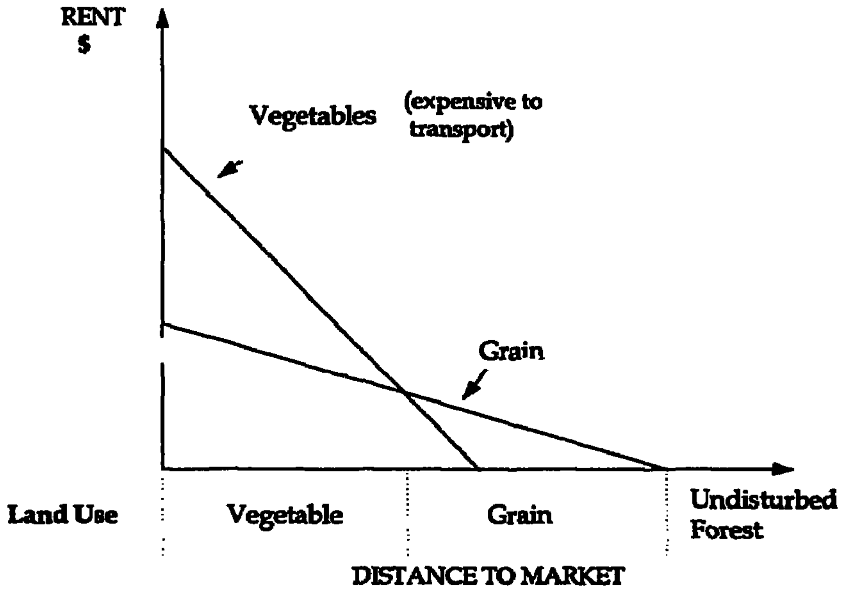
Southgate, Sierra, and Brown (1991) examine deforestation in Ecuador with a reduced-form model similar to that presented in this paper, but use canton-level data. They regress agricultural population on urban population, road length, and soils. In a separate equation, deforestation is regressed on agricultural population and tenure security. Deforestation is strongly linked to agricultural population, which in turn is positively correlated with soil quality and with road length. The model does not however control for the endogeneity of agricultural population, or allow for the influence of roads on deforestation independently of their effect on population.

3.0 A spatial model of land use

Deforestation is just one aspect of a general model of land use. The model to be estimated traces its ancestry back to von Thünen (1826). Theoretical variants have been presented by von Amsberg (1994), Schneider (1994) and Hyde *et al* (1993). The only econometric implementation of which we are aware is a US application by Alig (1986). Fox *et al* (1994) present a formally similar econometric model of crop choice by Thai farmers, but without appeal to an economic model.

The basic idea is straightforward. (See Figure 1). There is a potential rent (farmgate value of output minus costs of inputs) attached to each possible use of each possible plot of land. The model predicts, simply, that land will tend to be devoted to the activity yielding the highest rent. Thus, in the classic example, farmers near a city find vegetables more profitable than grain. But because of perishability, it is more expensive to transport vegetables than grain.

FIGURE 1 - THE MODEL: VON THUNEN REVISITED



At some distance from the city grain becomes more profitable than vegetables. Therefore, at a greater distance, where it is not economically feasible to transport any crop to the city, the land may be used by subsistence farmers. Further yet, the land may be undisturbed under its original forest cover.

The gist of the model is as follows. (A formal derivation of the model and its econometric implementation are given in Appendix A). The potential rent associated with devoting plot i to use or commodity k is[2]:

(1) Rent for k at i = (Farmgate price of k at i)*(Per-hectare production of k at i) - (Farmgate price of inputs to k at i)*(Quantity of inputs to k at i)

Unfortunately we observe none of these variables. We do however observe the determinants of price and of productivity and can therefore formulate a reduced form model[3]. First, following von Thünen, we assume that farmgate price of outputs decreases with distance from market. We assume that input prices increase with distance from market. This should certainly be true for manufactured inputs such as fertilizer. Labor costs, too, should be relatively higher at greater distances from market centers, where population density is lower and workers require compensating differentials to reflect the paucity of amenities (health, education, entertainment).[4] We distinguish two dimensions of distance: the distance to the nearest road, and the travel time along that road to the nearest market. For each commodity we can then specify two functions:

(2) Farmgate price of k at i = P_k (distance to road at i, on-road travel time to market)
Farmgate price of inputs to k at i = C_k (distance to road at i, on-road travel time to market)

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[2] This assumes a static framework. Dynamic issues are discussed below.

[3] Note that all the right hand side variables are jointly determined with land use in a spatial equilibrium and therefore endogenous to the model. Hence, to estimate (1) directly, we would have to instrument these variables via auxiliary equations parallel to those used to derive the reduced form.

[4] On the other hand, higher urban costs of living could result in a negative gradient of wages as distance from town increases.

The productivity of plot i for commodity k will depend on land characteristics at i. These include the nutrient content of the soil, acidity, workability, drainage, susceptibility to flood, and slope:

(3) Per-hectare productivity of k at i = S_k(land characteristics at i)

With suitable assumptions about functional form (see Appendix A), equations (2) and (3) are substituted into (1), yielding:

(4) ln Rent for k at i = $\alpha_{0k} + \alpha_{1k}$ distance to road + α_{2k} on-road time to market + α_{3k} (measure of agricultural suitability for k) + ...+ u_{ik}

Given the assumptions, the coefficients on distance are unambiguously predicted to be negative, and those on land characteristics will be consistent with the characteristic's predicted effect on productivity. Note that a random disturbance term, u, has been added. This represents the effect of unmeasured variables.

Finally, we add the assumption:

(5) Plot i is used for commodities k if: rent for k at i> rent for any other commodity at i

This is a strong assumption, with the following underpinnings:

Land use is reversible. If cultivated land becomes uneconomic (due to a drop in crop prices, say), it will revert to natural vegetation. This is a defensible assertion, even in the short run, as long as "natural vegetation" is broadly defined. If "forest" were distinguished as a separate land use, reversibility certainly would not hold in the short run, since abandoned land takes years to return to forest. For many but not all forest areas, reversibility might be a reasonable assumption in the context of a long-run, static equilibrium model. Large portions of Belize's forest, for instance, were in the recent past levelled by hurricanes. Studies in the Amazon, too, have shown that most abandoned plots quickly revert to forest (Moran *et al.* 1994), though this is less true of plots which have been intensively used or scraped by bulldozers (Nepstad *et al.* 1991). It is important to stress, though, that deforestation is only one form of forest degradation. Regrowth of forest cover, for instance, does not necessarily imply maintenance of original biodiversity levels.

Tenure as a determinant of rent. Equation (5) assumes that landowners will either adopt the highest-rent land use, or rent or sell the land to someone else who will do so. But, as Schneider (1994) and Hyde *et al.* (1993) have stressed, returns to different land uses depend strongly on tenure. On the frontier, where land rights are poorly defined and difficult to defend, it may not be profitable to invest in perennial crops. Given tenure security, however, perennials may represent the highest value use of the land. Similarly, largeholders may refrain from renting out land to sharecroppers, even where the latter enjoy higher returns, if land tenure might thereby be jeopardized. Hence it is desirable to use the land's tenure status as an explanatory variable in equation (3).

Future price changes are controlled for. If today's land use affects tomorrow's land productivity or tenure, then the future price-paths of alternative products will affect current land use decisions. A classic example is deforestation as a means of asserting land rights in an area where land prices are expected to rise. (Schneider 1994) Ideally, then, the expected path of future prices should be included as explanatory variables.Given (5), and assumptions about the statistical properties of u, statistical methods can be used to find the coefficients for (4) which best explain observed patterns of land use. One convenient, but very strong, set of assumptions (see Appendix A) leads to a multinomial logit model, which here yields a very simple formula[5]:

(6) Predicted probability that plot i is used for:
k = (predicted rent for k at i)/(Sum of predicted rents for all possible uses j at i)

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[5] For technical reasons, the coefficients of (4) for one land use are normalized to zero.

Equivalently, under this formulation equation (4) describes not just the ln rent for k, but also the ln odds that plot i is devoted to k relative to a baseline use (e.g., undisturbed vegetation.)
The multinomial logit model, however, requires that the unobserved effects on the rent for commodity k be independent of the unobserved effects for other commodities at the same point. This is implausible; unmeasured aspects of soil fertility, for instance, may have similar effects on a variety of alternative crops. In future work, a multinomial probit formulation will be applied. This allows for correlation among the unmeasured effects, but is computationally much more complex and can handle only a limited number of alternative uses.

3.1 Dealing with endogeneity

We would like to interpret the results of the model as telling us the effect of the road network on agricultural land use. This interpretation would be straightforward for roads whose placement was not motivated by agricultural development prospects. For instance, some roads are installed for political reasons, or to provide access to a mine site, or to connect distant cities.

In general, however, road construction and routing may be endogenous -- that is, influenced by agricultural development considerations. If roads tend to be preferentially routed through agriculturally suitable areas, and if some aspects of suitability are not observed, then the model will tend to overestimate the effect of distance from the road. A plot of land may be undeveloped not because it is far from the road; it may be far from the road because it is not suitable for development.

There are two solutions to this problem. One, used here, is to employ data which provides a rich set of variables to control for agricultural suitability. By explicitly controlling for the most important determinants of agricultural suitability, potential bias is greatly reduced.

Ideally, it would be desirable to instrument the distance variables. In this approach, distance to road, and on-road distance to market are modelled as functions of instrumental variables which are maintained to be independent of unmeasured aspects of agricultural suitability. Predicted values of the distance variables are then used in equation (4) to predict land use. Because the predicted values are, by hypothesis and construction, "purged" of endogeneity, the resultant estimates are unbiased. This strategy is appealing but difficult to implement because of the difficulty of finding appropriate instrumental variables. Appendix B discusses the instrumentation strategy further, reviewing one ineffective approach and nominating a promising alternative for future experimentation.

3.2 Spatial autocorrelation

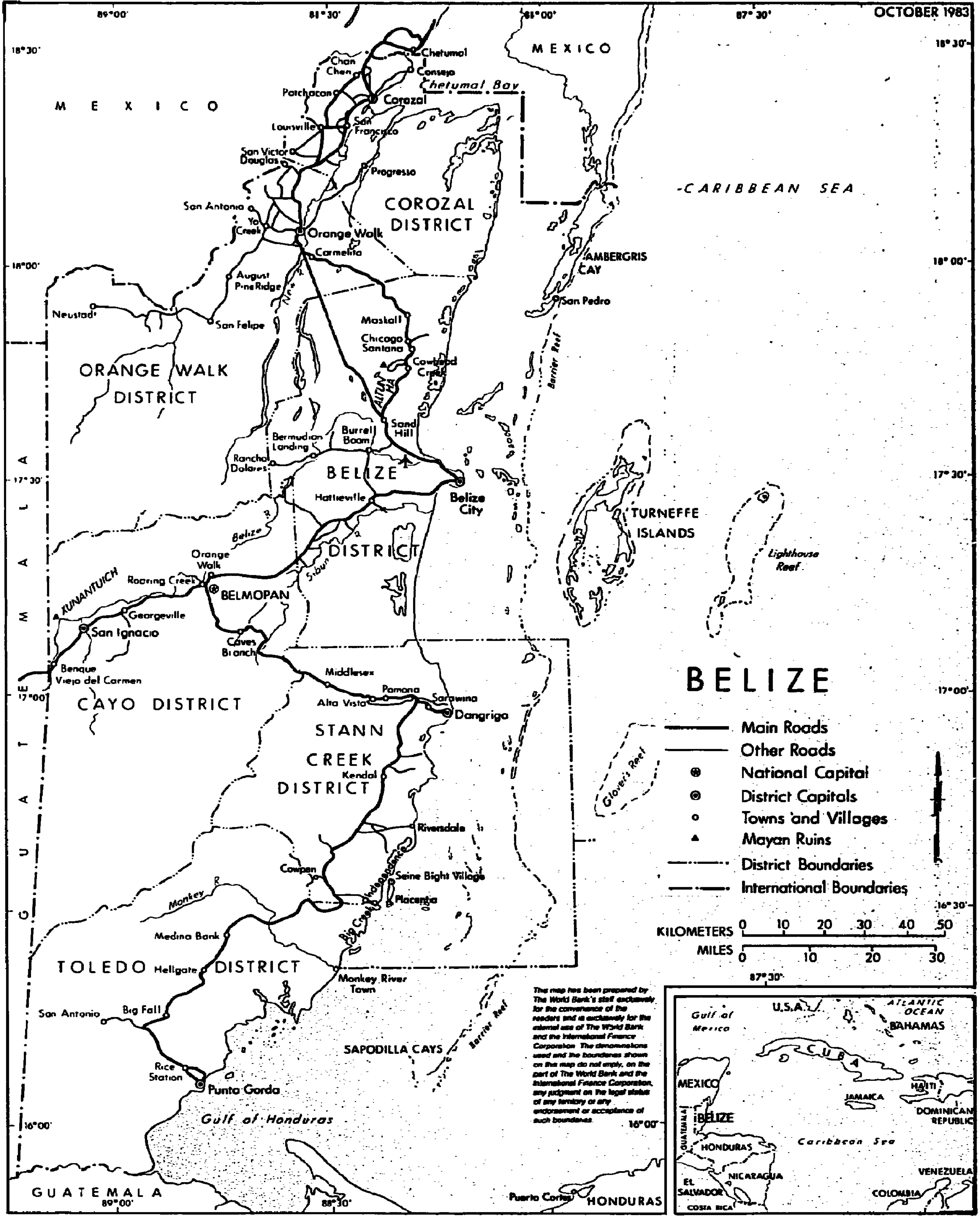
Land characteristics are quite likely to be characterized by spatial autocorrelation: places that are close by will tend to have similar soil types, rainfall, and so on. Some of these characteristics may not be observable. The resulting spatial autocorrelation of disturbance terms (the u_{ik} in equation 4) is the two-dimensional analog of more familiar patterns of autocorrelation in time-series models. In general, it results in inefficient parameter estimates and inaccurate measures of statistical significance.

Methods exist for dealing with spatial correlation in linear models (Anselin 1988). A computationally complex algorithm has been proposed for binary logit models (McMillen 1992) but no equivalent exists for the multinomial logit or probit models considered here. If however, we assume that the combined effect of the unobserved variables varies smoothly over the landscape, then a spatial trend can be used to remove autocorrelation. The two-dimensional equivalent of a time trend, this consists simply of a polynomial in latitude and longitude.

4.0 Land use in Belize: context and relevance

Belize is a small country, with about 200,000 inhabitants and about 22,000 square kilometers of land area. As Map 1 (IBRD 17093RI) shows, only about 12% of the land area has been converted to agriculture or settlements; 65% is under broadleaf forest, the remainder consisting mostly of swamp, pine forest, and mangrove forest. (See Map 2; Table 1 gives a more disaggregate breakdown of land cover)

IBRD 17093R1
OCTOBER 1983



LAND COVER 1989/92

MAP 2

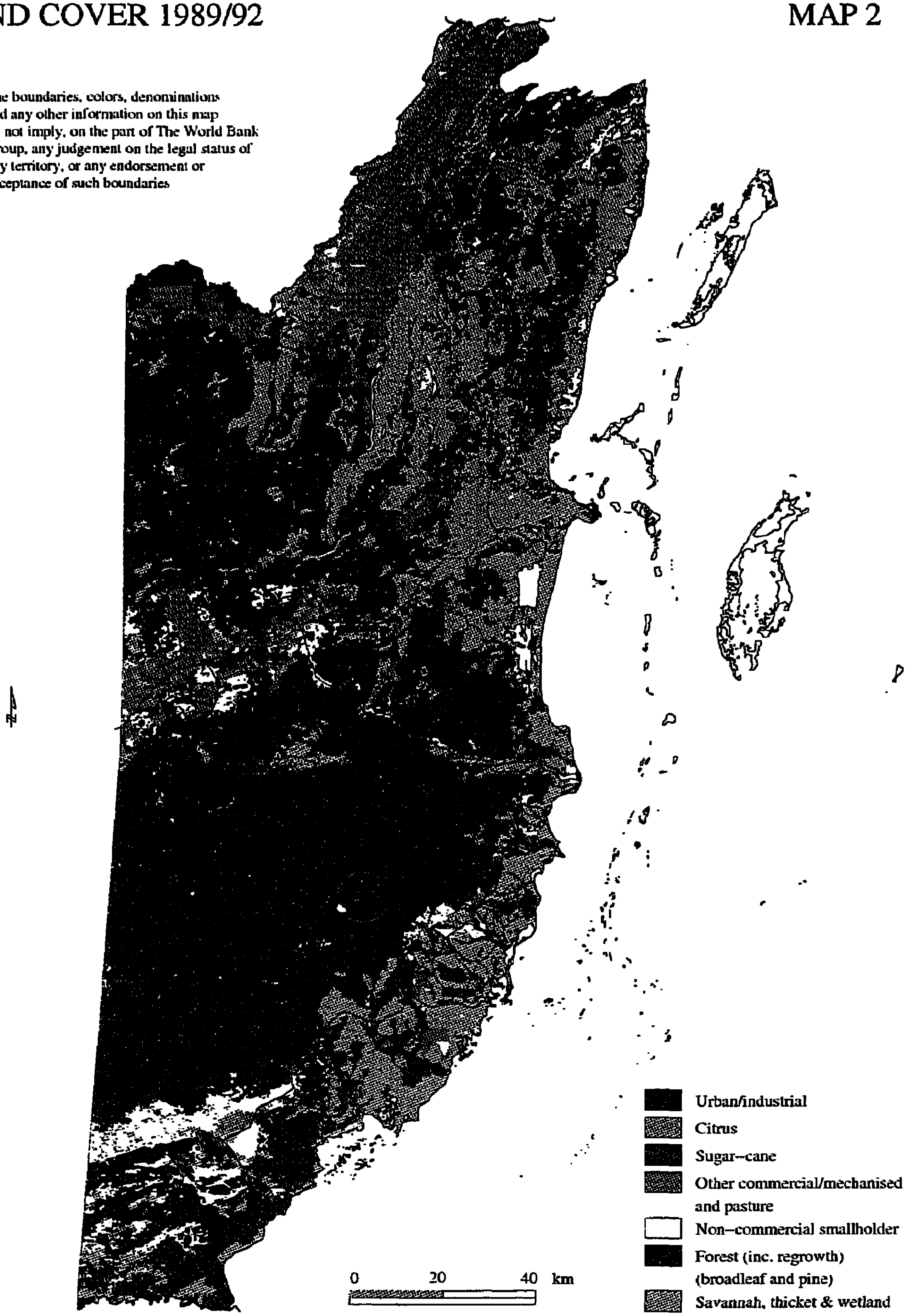


Table 1: Land use in Belize, 1989/92

Land Use	Area (Ha)	Percentage of Total Land Area
Urban/industrial	**8355**	**0.38**
Sugar-cane	**64072**	**2.95**
Citrus	**12963**	**0.60**
Annual crops (mechanized)	40246	1.85
Bananas	2058	0.09
Mango	1654	0.08
Cocoa	202	0.01
Cashew	34	0.00
Pasture	35622	1.64
Other commercial crops	**79815**	**3.67**
Milpa farming	37162	1.71
Annual crops (non-mech.)	19619	0.90
Semi-subsistence	**56781**	**2.61**
Broadleaf forest (inc regrowth)	1429921	65.77
Pine forest	64881	2.98
Forest (inc. regrowth)	**1494802**	**68.75**
Savannah	192192	8.84
Thicket	84773	3.90
Herb. and shrub	18844	0.87
Bamboo/riparian	11518	0.53
Coastal strand vegetation	2481	0.11
Mangrove	31255	1.44
Saline swamp	34460	1.58
Marsh swamp	41931	1.93
Bare ground	765	0.04
Savannah, thicket, wetland	**418218**	**19.24**
Water bodies	**39181**	**1.80**
Total	**2174187**	**100.00**

Despite its small size, Belize is a reasonable exemplar of many of the issues and circumstances of deforestation. First, its population/forest area ratio, while low, is of the same order of magnitude as a number of important forest regions, including Bolivia, the Congo, Gabon, Papua New Guinea, and the states of Amazonas and Pará (See Table 2).

Table 2: Population compared to forest cover

Region	People/ km2 forest	c. 1990 Population thousands	1990 Forest area 000 ha
Amazonas	1.3	2089	154842
Belize	**9.5**	**190**	**1996**
Bolivia	14.5	7170	49317
Brazil	26.6	149040	561107
Congo	11.2	2230	19865
Gabon	6.4	1160	18235
Papua New Guinea	10.8	3880	36000
Pará	4.6	5085	110073
Suriname	2.8	420	14768

Sources:
WRI, World Resources 1994-95
except: Brazilian state populations (1991): Statesman's Yearbook 1994/95
Brazilian state forest cover: FAO FORIS database

Second, Belize is highly biodiverse, boasting for instance 528 bird species, as compared to 650 for the U.S. (WRI 1994). While endemicity (the number of unique species) is low, Belize's long-run conservation importance is linked to its large tracts of contiguous forest (important for wide-ranging species such as the jaguar) and to the rapid rates of deforestation in neighboring countries. Third, the forests of Belize are facing increasing pressure from agricultural development. The past twenty years have seen a significant influx of refugees (up to 25,000 according to King *et al.*, 1993) from El Salvador and Guatemala. These immigrants, who primarily practice subsistence agriculture, have settled around the Maya mountain block, significantly increasing pressure on land and forest resources in these areas. Recent immigration across the Western border from the Peten region threatens the integrity of the Chiquibul National Park and the adjoining Forest reserves. At the same time, a booming citrus market and increased road construction have encouraged the spread of commercial agriculture away from the processing facilities. Fourth, because much agriculture is directly or indirectly supported, policy changes could increase or relieve pressures for agricultural conversion.

To set the modeling work in context, we briefly review below the main features and trends in land use and land tenure.

4.1 Agricultural land use[6]

Sugar. The largest single agricultural land use is sugar, at 51,000 ha[7]. Unusually for the Caribbean, it is grown mostly by smallholders. Sugar has been cultivated in northern Belize since the mid 1850's, when refugees from the Yucatec Caste Wars in Mexico initially provided the labor supply which made cultivation possible. Cultivated area expanded rapidly with the establishment of a large processing plant in the 1950's and a second in 1967. Belize is a high-cost sugar supplier. Per hectare yields are low, and the product must be barged along the coast to Belize City, where it is transferred to ships berthed offshore. (Belize City lacks a deep-water harbor). The industry is supported by a variety of preferential trade agreements.

Pasture. Approximately 33000 ha are devoted to pasture, by both small and large holders. Most beef is for domestic consumption. The industry enjoys tariff protection.

Mechanized farming . Largeholders, many of whom are Mennonite immigrants, devote about 41000 ha to mechanized annual crops, primarily maize, rice, and red kidney beans.

Miilpa. Milpa is the local form of slash-and-burn agriculture, practiced primarily by Mayan Indians and by Hispanic immigrants. About 40,000 ha are under active milpa cultivation, primarily in the southern part of the country. The total area affected is much larger, however,

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[6] This section draws heavily on King *et al.* (1993).

[7] Land use figures in this section are from the 1989/92 land use survey and may differ from Ministry of Agriculture reports.

because the land is rotated under forest fallow. Maize is the most important crop, produced primarily for self-consumption. Rice is also important. Although the price is supported by the Belize Marketing Board, financial analysis suggests that the imputed wage rate for dryland rice cultivation is below the going wage for unskilled labor (even assuming zero returns to land) (King *et al.*, 1993, p. 130). Milpa cultivation is likely to increase rapidly over the coming years if high rates of immigration continue. This could result in increased competition for land among subsistence farmers, and encroachment into protected areas.

Other non-mechanized annual crops. These cover approximately 20,000 ha and are primarily located near towns. It is possible that there is cross-classification error between these crops and milpa cultivation; in some cases a farmer may cultivate both kinds of crops.

Citrus. The 1989/92 land use survey identified about 13,000 ha under citrus: too small an area to be accorded a distinct class in the land use model estimated below. However, citrus cultivation is growing rapidly. The area under cultivation is estimated to have more than doubled between 1985 and 1990 (King *et al.*, 1993, p. 33). Cultivation is expected to increase further with the upgrading of the Hummingbird Highway (Belmopan-Middlesex) and the Southern Highway (Dangriga-Punta Gorda). While Belize has enjoyed preferential access for citrus concentrates to the US market, its competitive position may be threatened by Mexico under NAFTA. Lack of a deep water harbor and a lower scale of production place Belize at a disadvantage.

Other export crops. Other crops, while of potential economic importance, occupy comparatively little area. Bananas occupied about 2300 ha; mango, cocoa, and cashew another 1900 ha.

Forestry. Belize has exported timber for more than two centuries. Interestingly, though, logging has had little significant impact on forest area. This is because logging has always focused on selective extraction of very high value species: logwood (used for dyes), mahogany and cedar. Extraction has tended to employ relatively low-impact methods. Railways and roads built for timber extraction did not catalyze agricultural development; in many cases roads and rail lines have reverted to forest. Logging activities have, however, severely depleted the stock of mahogany and cedar (Alder, 1993).

4.2 Land tenure

Land tenure in Belize has a strong effect on land use. Table 3 shows a breakdown of Belize's land area according to tenure. About 22% of the country is National land, state land inherited by the government in the late nineteenth and early twentieth centuries following the failure of the large private logging estates. This land is available for lease and eventual purchase and has traditionally been viewed as a land bank by successive governments. This is being gradually disbursed in line with constitutional guarantees concerning the rights of Belizeans to both own and 'enjoy fully' a piece of land. Unleased portions of national land are thought to be more susceptible to extralegal conversion (for instance to subsistence agriculture) than other areas. Another 40% of the land area is privately owned land and is less likely to experience squatting. About 14 % of Belize is currently protected as a national park, wildlife sanctuary, nature reserve or private reserve with a further 20% being held as Forest reserve. The latter is increasingly under threat from agricultural incursion and periodic excision by government. Finally, around 1% of Belize falls within Indian reservations. Use-rights to these lands have traditionally been allocated by Maya community groups.

Table 3: Land area by tenure class

Status	Area(Ha)	Percent (%)
Forest reserve	451133	20.46
Protected areas	312063	14.15
National land	479478	21.75
Indian reserve	26114	1.18
Private land	890378	40.39
Total	**2159166**	**97.93**

The difficulties traditionally associated with communal land tenure combine with physical and cultural factors to ensure that a comparatively high proportion of these lands are devoted to milpa.

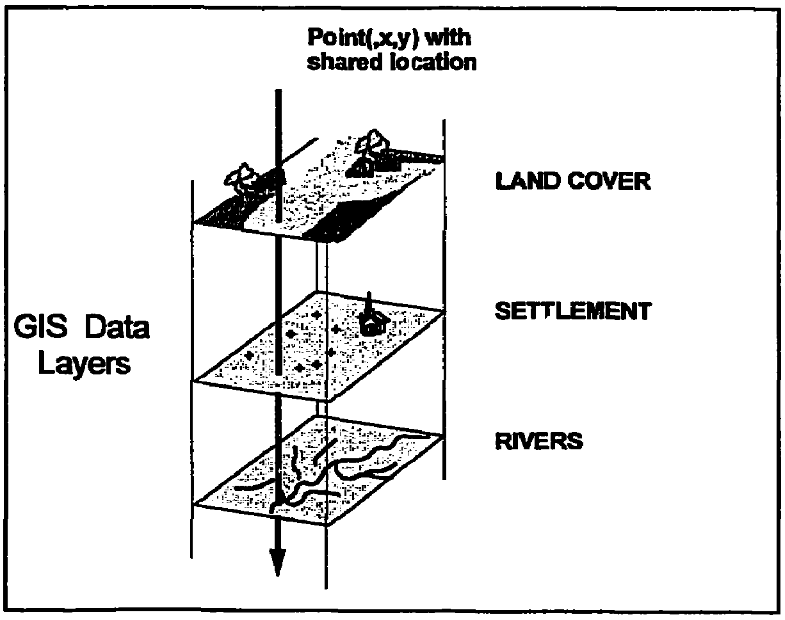
5.0 Data

5.1 Data framework

We estimate the model of equation (4) using data on a sample of points of land. This information is derived from a GIS (Geographic Information System) database: that is, digitally coded maps representing a variety of land characteristics of interest. Sampling was performed using a 3-km rectangular grid (see Map 3), yielding 2401 mainland points with data on land cover. Of these, 46 water and urban points were excluded from the sample.

To visualize the data extraction process, imagine stacking the data layers (maps) of interest. A pin pierces the stack at each sample point, and the mapped information for the point -- slope, distance to road, soil quality -- is recorded and collated. (See Figure 2) In practice, we were concerned that the data layers might be slightly misregistered. To minimize problems of misregistration, we pierced the data layers with a virtual apple corer rather than a virtual pin.

Figure 2 - The Data Framework

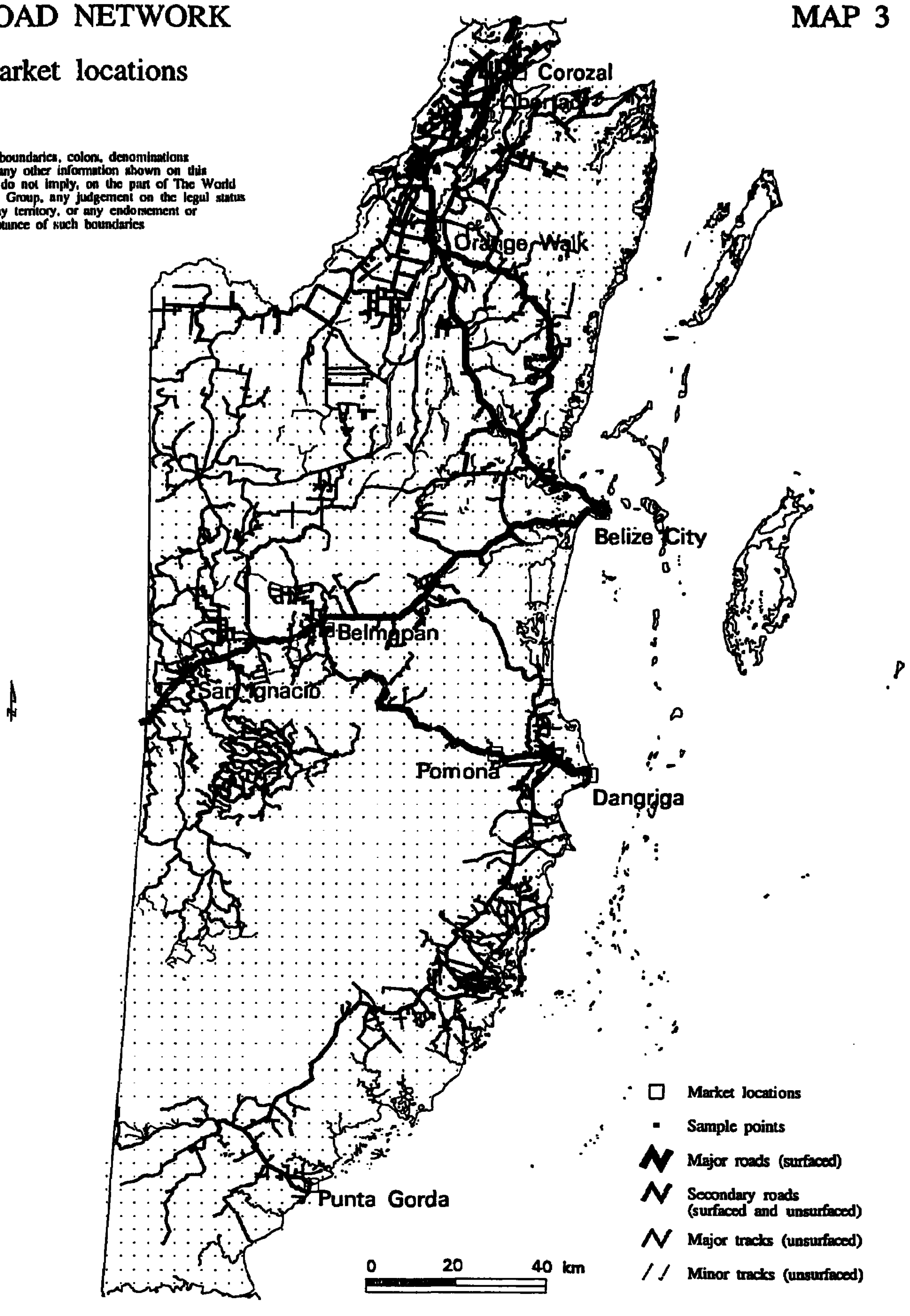


ROAD NETWORK

MAP 3

Market locations

The boundaries, colors, denominations and any other information shown on this map do not imply, on the part of The World Bank Group, any judgement on the legal status of any territory, or any endorsement or acceptance of such boundaries



That is, we created a 100-meter diameter buffer (circle) around each sample point on each data layer, and coded the characteristic which dominated the buffer[8].

The data layers are described below. All were made available by the Land Information Centre (LIC) of Belize's Ministry of Natural Resources.

5.2 Land use data

Land use or land cover constitutes the model's dependent variable. The data are derived from a recent study (LIC, 1994) by the Lands and Surveys Department of the Ministry of Natural Resources with assistance from FAO. These land use maps, with a scale of 1:50,000, were produced through interpretation of scaled false color prints of SPOT multispectral data. Interpretation involved considerable ground-truthing. In order to obtain cloud-free imagery, it was necessary to use SPOT data ranging from 1989 to 1992, so the resulting map does not carry a single date.

The map describes a total of 31 categories of land use/land cover. As in many studies of this nature, difficulties occurred in defining distinct classes (particularly in the savanna/thicket/shrub areas) and figures given to represent broadleaf forest cover are known to include a considerable amount of secondary regrowth (7 years and older). Often two agricultural uses would be intermingled or be otherwise hard to distinguish. For instance, mechanized annual crops and pasture tended to be associated. For the purposes of this study, only a very aggregate classification was needed. Milpa and non-mechanized annual cultivation were classed as "semi-subsistence"; all other agriculture, together with a small amount of land cleared but not under cultivation, was classed as "commercial"; and all other areas, including secondary regrowth (but excluding water bodies and settlements) were classed as "natural vegetation"[9].

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[8] This precaution was probably unnecessary. In the case of land cover, for instance, 85% of the buffers were homogenous, and a single land use accounted for more than 70% of the area in 95% of all buffers.

[9] Almost all the "natural" vegetation in Belize has been modified by human action. The category names are for convenience only.

5.3 Land systems data

The land systems data describes the soil's physical and chemical characteristics. These data are taken from a series of Land Resource Assessments (King *et al.* 1986,1989,1992), which were designed to yield planning information on the land's suitability for alternative crops.

The Land Resource Assessments were based on a combination of aerial photography and field surveys. The methodology involves segmenting the landscape into microregions, based on agricultural potential as predicted from topography, soils, and vegetation. The land systems map is segmented into about 10,000 of these microregions, which fall into 350 distinct classifications, called land subunits[10]. Each subunit is characterized by a set of physical and chemical descriptors, which in turn are used to assess suitability for each of 19 agricultural land uses. It is important to stress that nutrient values are derived from field sites which are not in agricultural use. These values are then imputed to occurrences of the same land subunit which are under cultivation.

For the purposes of this analysis, it was sometimes necessary to assign point values to a variable (such as pH) where the land systems classification assigned a range. In other cases -- especially for categorical variables -- the values were aggregated so as to constitute binary dummies.

Land systems variables used in this analysis are as follows. (Original coding and other information are in King *et al.*, 1993, pp 110-117).

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[10] These are similar to the land facets commonly associated with the land systems methodology.

SLP25PL --Dummy variable, slopes 25 degrees or higher. (From a 6-category slope descriptor.)

FLOODHAZ -- Dummy variable for flood hazard. Floodhaz=0 for areas where floods occur less frequently than every 20 years, or for high floodplain bench backland. Floodhaz=1 for all other areas. (Original variable: 16-category flooding risk.)

SANDY -- Dummy for sandy soil. (Reclassified from base variable: sandy if moisture availability > 2)

STONY -- Dummy for stony soil. (Reclassified from base variable, workability; stony if workability = "stony or compact", "very stony", "25 to 50 cm to bedrock", "very stony and very shallow", "stony, very shallow and imperfect drainage; or very compact")

WORKABLE -- Dummy for soil which is "easily workable" (Reclassified from base variable, workability. Omitted categories - neither workable nor stony, are: "rather compact", "imperfect drainage", "poor drainage", "variably shallow".)

WETNESS -- An eight-point ordinal scale for drainage "as indicated by how the effect of poor drainage affects the growing of cacao, citrus, and pasture", ranging from 0="well-drained" to 7="permanently wet".

LOW_NITR -- Dummy for total nitrogen less than or equal to 0.2% .

AVAIPHOS - Available phosphorus in ppm, Bray for acid soils, Olsen for alkaline. Recoded at midpoints of 8 category scale.

PHLEVEL -- Soil pH, recoded at midpoints of 10 category scale.

5.4 Land tenure data

The land tenure data is the most current available. The following categories are distinguished: national parks, private reserves, forest reserves, national land, private land, Indian reservations. Areas designated national land include lands leased out. Some private lands may be misclassified as national land.

5.5 Distances to roads and market locations

Road network data is from a 1:50,000 topographic map series based on 1980's data, updated in certain areas to 1993[11]. For each sample point, *distance to road* is the straight-line distance to the nearest point on the road network. That "trailhead" point is then used as the basis for calculating the *on-road travel time* to the nearest town. The on-road travel time from the "trailhead" to each town is based on the optimal (time-minimizing) route, as determined by the NETWORK module of ARC/INFO, the GIS software used in this project. In computing travel times, estimated travel speeds[12] were assigned to each class of road, as follows:

Class	Description	Est. maximum speed (mph)
1	Major roads (surfaced)	65
2	Secondary roads (surfaced/unsurfaced)	45
3	Major tracks (unsurfaced -passable all year	35
4	Minor tracks (unsurfaced - passable in the dry season)	20

Towns used for distance calculation are Belize City, Belmopan, Corozal, Dangriga, Orange Walk, Punta Gorda, and San Ignacio. These comprise the national capital and district headquarters, and are the only sizeable settlements in the country[13].

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[11] It would have been preferable to recreate the road network as of 1989, the earliest date for the land use data. This will be attempted in future work, using satellite imagery.

[12] For the purposes of the model it is sufficient that the interclass ratios of these speeds be approximately correct. In future work we will attempt to incorporate engineering estimates or observed traffic data.

[13] In addition, for each sample point we calculated the on-road distance to Pomona (site of the citrus-processing plants) and to the nearest sugar-processing plant (the closer of Libertad and Orange Walk), but these were not used in the final model.

6.0 Results of estimation

6.1 Coefficient estimates

The multinomial logit model was estimated for a three category classification of land use: natural vegetation; semi-subsistence farming (including milpa and nonmechanized annual crops); and commercial farming (primarily sugarcane, mechanized annual crops and pasture, with some citrus, bananas and minor agricultural land uses). National parks and private reserves were excluded from the sample, because only one of the 322 sample points in these classes was used for agriculture[14].

The results are shown in Table 4 with variable means reported in Table 5. The overall estimate is significant at the p=.0001 level. The coefficients for natural vegetation, the comparison class, are normalized at 0.

Both agricultural land uses imply strong declines in rent with increasing *distance from the road*. The decline is much sharper for commercial farming, however. Similarly, *on-road distance* to market depresses rent more rapidly for commercial farming than for semi-subsistence farming (the small absolute difference in the coefficients on distance squared results in a substantial difference in impact.)

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[14] In effect, we assign an infinite negative coefficient to indicators for these classes, which is, for all practical purposes, the maximum likelihood estimate.

Table 4 - Multinomial logit estimate of land use

```
                                                 Number of obs =    2021
Multinomial regression                           chi2(40)      =  671.58
                                                 Prob > chi2   =  0.0000
Log Likelihood = -518.19933                      Pseudo R2     =  0.3932
------------------------------------------------------------------------
                                      Coef.   Std. Err.        z    P>|z|
------------------------------------------------------------------------
SEMI-SUBSISTENCE FARMING (MILPA AND OTHER NONMECHANIZED)

 slp25pl DUMMY, SLOPE > 25          -.7597318  .4892326   -1.553   0.120
floodhaz DUMMY, FLOODHAZARD          .5973458  .4083262    1.463   0.143
   sandy DUMMY                       .9873418  .5682349    1.738   0.082
   stony DUMMY                      -.6283948  1.183857   -0.531   0.596
workable DUMMY                      -.7156817  .5879095   -1.217   0.223
 wetness 8 POINT ORDINAL SCALE      -.2856389  .1024821   -2.787   0.005
natlland DUMMY, NATIONAL LAND        .7025545  .3448903    2.037   0.042
low_nitr DUMMY, NITROGEN < 0.2%     -1.433593  .4144497   -3.459   0.000
avaiphos AVAILABLE PHOSPHORUS, PPM   .0425456  .0338525    1.257   0.209
 phlevel PH                          5.062912  2.277653    2.223   0.026
phlevel2 PH SQUARED                 -.4143897  .1987818   -2.085   0.037
 d_to_rd KM TO ROAD                 -.4435889   .186327   -2.381   0.017
 ds_tord KM TO ROAD, SQUARED         .0067064  .0210698    0.318   0.750
 d3_town ON ROAD TIME TO NRST TOWN   -.062215  .0230098   -2.704   0.007
 d3stown ON ROAD TIME, SQUARED        .000535  .0002576    2.077   0.038
       x X-COORDINATE               -.9751901  .3428826   -2.844   0.004
       y Y-COORDINATE                .5322553  .3089695    1.723   0.085
      xy                             .6364214  .2440257    2.608   0.009
     x_2                            -.3403938    .31772   -1.071   0.284
     y_2                            -.2012505  .0975561   -2.063   0.039
   _cons                            -341.2074  256.0914   -1.332   0.183
---------+--------------------------------------
COMMERCIAL FARMING (Sugar, mechanized food crops, pasture, citrus)

slp25pl  DUMMY, SLOPE > 25          -.9772169  .5160684   -1.894   0.058
floodhaz DUMMY, FLOODHAZARD          .3284057  .3194296    1.028   0.304
   sandy DUMMY                       .8330149  .3626363    2.297   0.022
   stony DUMMY                      -.1607761  .4406501   -0.365   0.715
workable DUMMY                      -.1541151  .3345063   -0.461   0.645
 wetness 8 POINT ORDINAL SCALE      -.1405025  .0654008   -2.148   0.032
natlland DUMMY, NATIONAL LAND       -.1526676  .2644397   -0.577   0.564
low_nitr DUMMY, NITROGEN < 0.2%      -.951181  .2620511   -3.630   0.000
avaiphos AVAILABLE PHOSPHORUS, PPM   .0603394  .0224646    2.686   0.007
 phlevel PH                          .2163639  1.302868    0.166   0.868
phlevel2 PH SQUARED                  .0230276  .1111243    0.207   0.836
 d_to_rd KM TO ROAD                 -.9344324  .1634352   -5.717   0.000
 ds_tord KM TO ROAD, SQUARED         .0480959  .0188488    2.552   0.011
 d3_town ON ROAD TIME TO NRST TOWN  -.0644578  .0210767   -3.058   0.002
 d3stown ON ROAD TIME, SQUARED       .0001011   .000276    0.366   0.714
       x X COORDINATE                1.414435  .2211969    6.394   0.000
       y Y COORDINATE               -.4319792  .1107751   -3.900   0.000
      xy                            -.7925672  .1037173   -7.642   0.000
     x_2                             .1247388  .1833633    0.680   0.496
     y_2                             .1822047  .0325773    5.593   0.000
   _cons                             176.7267  106.2071    1.664   0.096
------------------------------------------------------------------------
Note: Coefficients for comparison group (nonagricultural vegetation) set to
zero. Excluded from analysis: national parks, private reserves, towns, water
bodies
```

Table 5 - Variable means

```
Variable |     Obs        Mean   Std. Dev.        Min         Max
---------+-----------------------------------------------------
      id |    2021    11223.94    711.5796      10007       12513
 wetness |    2021    2.190995    2.425348          0           7
floodhaz |    2021    .4067293    .4913451          0           1
   sandy |    2021    .5299357    .4992266          0           1
workable |    2021    .2424542    .4286737          0           1
   stony |    2021    .0821376    .2746421          0           1
low_nitr |    2021    .5893122    .4920804          0           1
   steep |    2021    .1459673    .3531609          0           1
stpkarst |    2021    .0712519    .2573087          0           1
       x |    2021    320.4322      29.042      262.5       382.5
       y |    2021    1905.532     70.2906     1757.5      2042.5
      hi |    2021    .0554181    .2288512          0           1
 d_to_rd |    2021    3.086103    3.637712   .0009148    18.05557
      xy |    2021    611.5699    69.03314   461.3438    776.6663
     x_2 |    2021    103.5198    18.57537   68.90625    146.3062
     y_2 |    2021    3635.989    267.3133   3088.806    4171.806
 d3_town |    2021    33.71085    20.81417         .4      113.71
d3_sugar |    2021    102.5999    62.94123        .28      235.82
 da_town |    2021    28.83961    13.41683   1.398425    66.99571
da_sugar |    2021    102.9492    64.44148   .4420102    252.5397
avaiphos |    2021    7.521524    4.838087          3          25
natlland |    2021    .2063127    .4062021          0           1
 ind_res |    2021    .0133597     .114838          0           1
 natveg6 |    2021    .8852053    .3188529          0           1
 d3stown |    2021    1569.437    1871.254        .16    12929.96
d3ssugar |    2021    14486.38    14496.31      .0784    55611.07
 ds_tord |    2021    22.75043    48.17415   8.37e-07    326.0036
 slp25pl |    2021    .2172192    .4124551          0           1
 phlevel |    2021    5.715064    .9828046        3.5         8.3
phlevel2 |    2021    33.62739     11.2711      12.25       68.89
  pnatvg |    2021    .8852053    .1791577   .1151127    .9999737
  pmilpa |    2021    .0301831    .0775559   3.12e-08    .7695376
pcomfarm |    2021    .0846116    .1664975   1.58e-06    .8846226
```

These results are plausible. Commercial farmers are likely to be highly sensitive to road and market access. This will be particularly true for sugar farmers, where typical transport costs range from $10-$18 per ton, against mill prices of $55. (King *et al.*, 1993) Milpa and other small farmers may market only a fraction of their produce, making them less sensitive to distance to market and to road. For crops they do market, transport costs may be less important. Typical transport costs for dryland maize in Toledo district, for instance, are just 5.6% of mill price[15]

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[15] Of course, the transport cost ratio may increase dramatically with off-road distance.

(King *et al.*, 1993). Nonetheless, semi-subsistence farmers may value access to schools, clinics, and off-farm employment sites.

The predicted impact of soil chemistry also appears to be plausible. *Nitrogen* has a strong, highly significant effect. It is relatively more important for semi-subsistence farmers, either because of differing crop mixes or because of credit constraints in purchasing fertilizer[16]. Soil acidity (as measured by *pH*) has a strong, highly significant negative effect on bid rent for semi-subsistence farming.

The log odds in favor of semi-subsistence farming increase by 2.8 as pH increases from its minimum of 3.5 to an optimum at 6.1; above that point, more alkaline soils are predicted to be less desirable. Soil acidity also depresses rent for commercial farming (the two terms are jointly significant at the .05 level), but there is no penalty for alkaline soils. Finally, the point estimates for the effect of *available phosphorus* are positive -- highly significant for commercial farming, not significant at conventional levels for semi-subsistence farming. In general, these results are consistent with anthropological findings that traditional farmers use a variety of pedological and botanical cues to assess soil quality with considerable accuracy (see Carter 1969 on Maya farmers in Guatemala; Wilken 1987 on Mexican and Guatemalan farmers; and Moran 1993 on Brazilian farmers).

Turning to other land characteristics the effect of high *slopes* on rent is negative for both land uses, as expected. The coefficient for semi-subsistence farming is just shy of significance at the .1 level and is smaller in absolute value than that for commercial farming. While far from conclusive, this is consistent with hilly land being relatively better suited for nonmechanized than mechanized farming. *Wetness* has a substantial and highly significant negative effect on rent for both land use categories. The effect is however twice as strong for semi-subsistence farming, perhaps because wetter soils are relatively harder for nonmechanized farmers to work.

---

[16] Alternatively, this may be a clue that soil nutrient deficiencies need to be interacted with distance in the equation; it is more expensive to remediate poor soils when they are further from the road.

Indicators for *sandiness* and *flood hazard* had estimated positive effects; sandiness was statistically significant. These variables may reflect the desirability of land near rivers. An indicator for *stony* soil had a negative coefficient, but, surprisingly, was not statistically significant. The only tenure variable included was *national land*, which had a strong positive effect on the value to semi-subsistence farming, as expected.

Finally, the *spatial trends* play a major role in fitting the model. For semi-subsistence farming, the standard deviation of the implied spatial effect is 2.1, with a range of 7; for commercial farming the standard deviation is 1.28, with a range of 3.2. The spatial effect for semi-subsistence farming has its peak in the Mayan Indian areas of Toledo district. The corresponding peak for commercial farming is near the sugar processing plants in the north. Linear and square terms in *distance to the nearest sugar processing plant* were jointly insignificant when added to the model because of high multicollinearity with the spatial trend variables.

To check the robustness of the multinomial logit model, binary logit and probit models were run. In these models, the two classes of agricultural use were combined, and additional explanatory variables were used[17]. The results for both specifications are qualitatively very similar to the multinomial logit results. Table 6 shows the binary logit results. In the binary model, it is possible to disaggregate high-slope land into non-karst and karst; the latter much more strongly discourages cultivation. It is also possible to add a dummy variable indicating high altitude (>400 meters). This too strongly discourages cultivation. The two tenure variables -- indicators for Indian reservation and for national lands -- have positive coefficients but are not statistically significant. The modest and insignificant net impact of these variables reflects strong but opposing impacts on subsistence versus commercial cultivation.

---

[17] Dummy variables which perfectly predict one but not both land uses (e.g., there is some subsistence agriculture but no commercial agriculture in Indian reservations) present estimation problems for standard software in the multinomial case, but are easily accomodated here.

Table 6: Binary logit estimates

Dependent variable: Agricultural use (n= 2021)

Variable	Parameter DF	Standard Estimate	Wald Error	Pr > Chi-Square	Chi-Square
INTERCPT	1	309.5	149.1	4.3103	0.0379
HI	1	-2.0896	1.0789	3.7512	0.0528
STEEP	1	-0.4310	0.4156	1.0756	0.2997
STPKARST	1	-1.2122	0.5440	4.9650	0.0259
FLOODHAZ	1	0.4384	0.2519	3.0299	0.0817
SANDY	1	0.6388	0.2861	4.9847	0.0256
STONY	1	-0.7560	0.4145	3.3274	0.0681
WORKABLE	1	-0.4376	0.2787	2.4660	0.1163
WETNESS	1	-0.2235	0.0542	17.0360	0.0001
LOW_NITR	1	-0.8151	0.2165	14.1778	0.0002
AVAIPHOS	1	0.0620	0.0179	12.0346	0.0005
PHLEVEL	1	-0.0551	1.1239	0.0024	0.9609
PHLEVEL2	1	0.0258	0.0962	0.0720	0.7885
IND_RES	1	0.5969	0.5283	1.2767	0.2585
NATLLAND	1	0.2007	0.2112	0.9031	0.3419
D_TO_RD	1	-0.7099	0.1181	36.1556	0.0001
DS_TORD	1	0.0289	0.0122	5.6291	0.0177
D3_TOWN	1	-0.0503	0.0155	10.5220	0.0012
D3STOWN	1	0.000198	0.000195	1.0366	0.3086
D3_SUGAR	1	-0.0341	0.0116	8.6042	0.0034
D3SSUGAR	1	0.000104	0.000049	4.5577	0.0328
X	1	0.5391	0.1435	14.1144	0.0002
Y	1	-0.4027	0.1555	6.7100	0.0096
XY	1	-0.4173	0.0845	24.4117	0.0001
X_2	1	0.3660	0.1660	4.8613	0.0275
Y_2	1	0.1386	0.0421	10.8563	0.0010

6.2 Predictive ability of the model

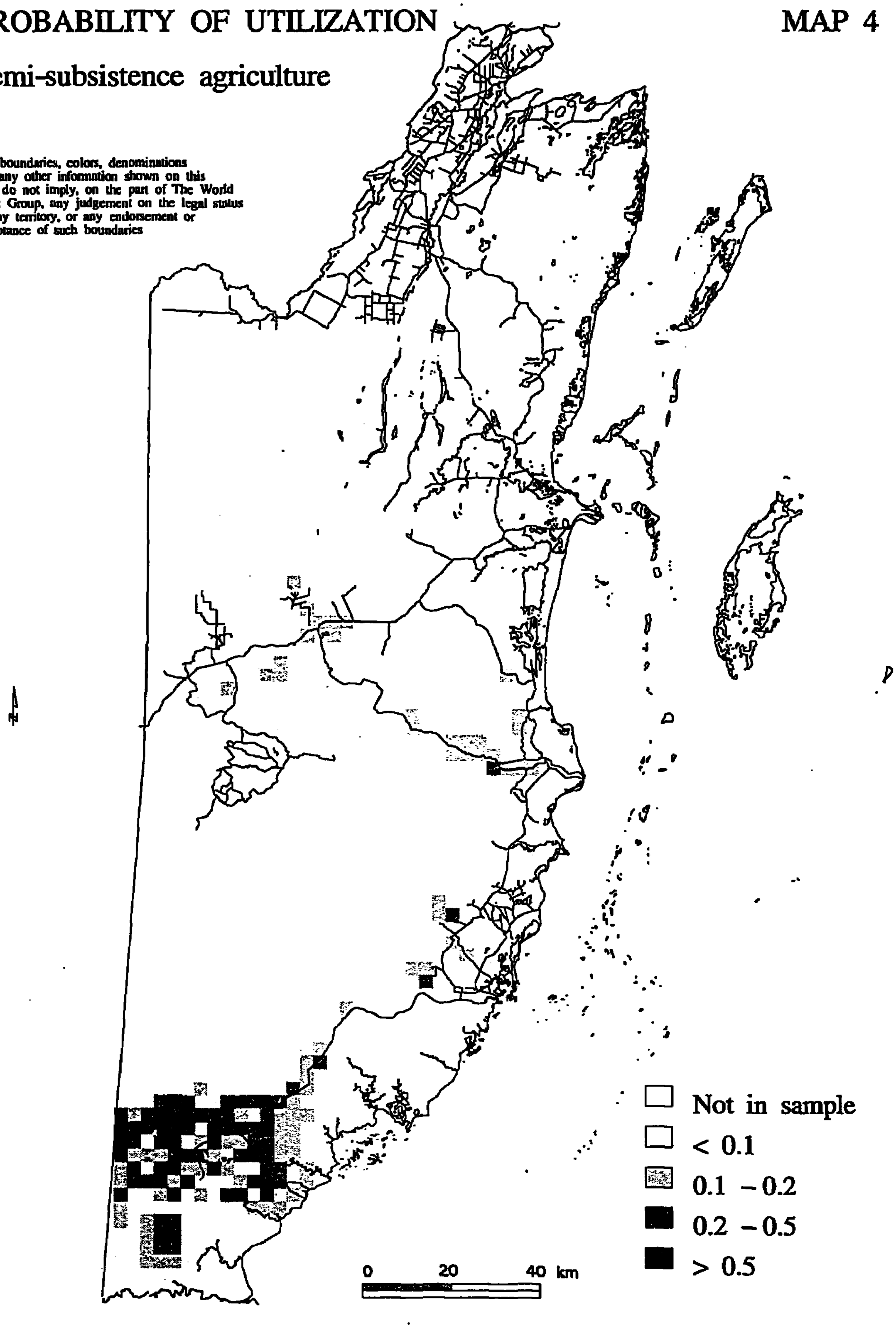
6.1 Spatial patterns

Maps 4 and 5 show the predicted probabilities of agricultural use over the landscape, for semi-subsistence and commercial agriculture. The probability peaks correspond reasonably well with the actual land use patterns shown in Map 2. The predicted commercial agricultural areas coincide with the sugarcane region of northern Belize, the mechanized farms of the northwest

PROBABILITY OF UTILIZATION

MAP 4

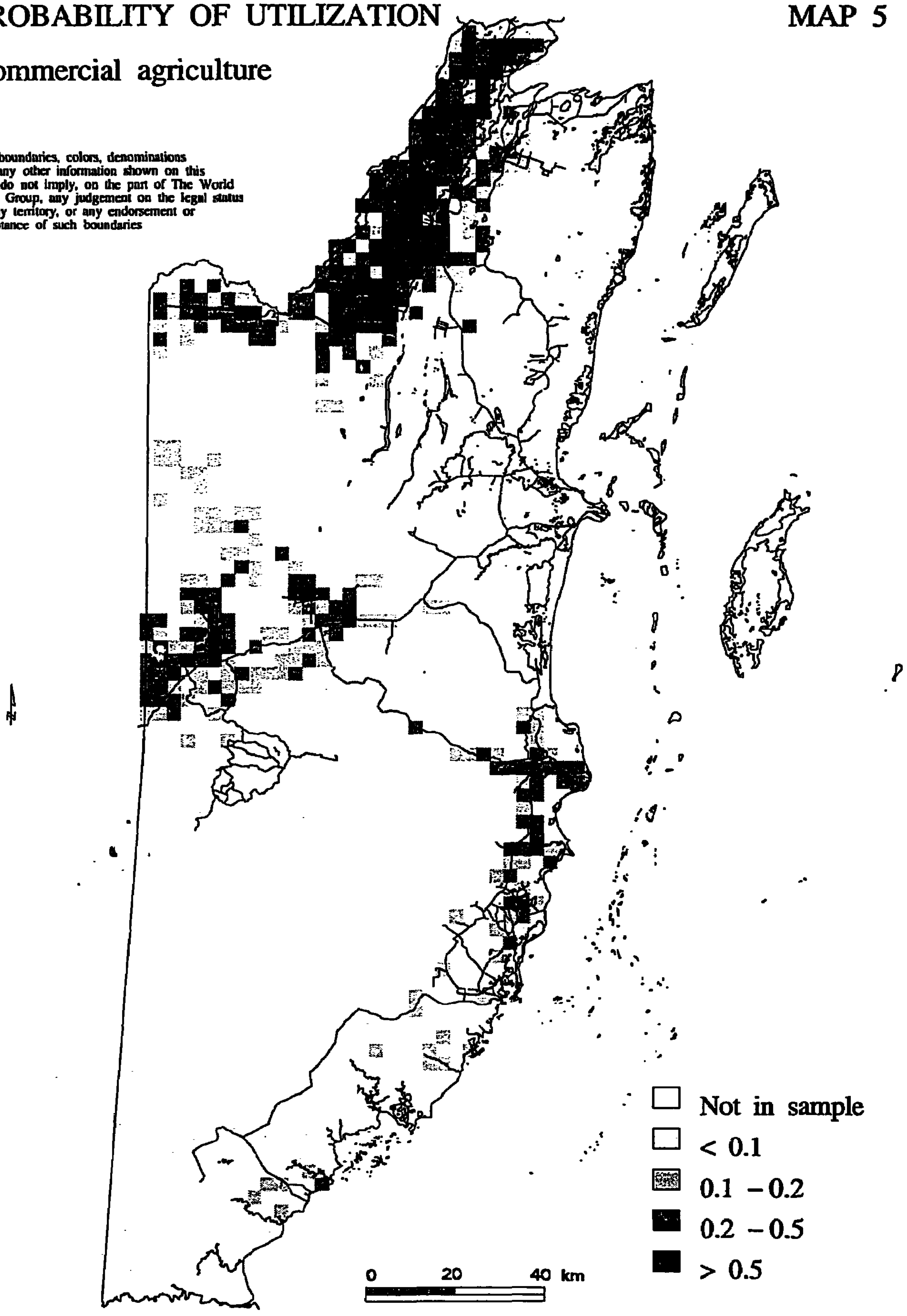
Semi-subsistence agriculture



PROBABILITY OF UTILIZATION

MAP 5

Commercial agriculture



and center-west (near San Ignacio), and the citrus-growing areas near Dangriga. The predicted semi-subsistence areas are centered on the actual subsistence farms of Toledo district, in the south.

Note that the model tends not to predict particular points as having very high probabilities of agricultural use; rather, it predicts entire areas as being predisposed, with each individual point having a modest probability of cultivation. Is this fuzziness a vice or a virtue? It is a vice if it reflects omission of important information which differentiates the agricultural suitability of neighboring points. It is a virtue if neighboring points are in fact very similar in agricultural suitability. In that case, it is truly a matter of chance which points are currently under cultivation.[18] This is particularly true for shifting cultivation, where fields are rotated between forest fallow and crops.

6.2 Classification accuracy

Because we argue that even low predicted probabilities of agricultural use convey information, we use a 20% probability as the prediction threshold (i.e., designate a point as predicted to be in agricultural use if the predicted probability is greater than 20%). Using this criterion, the model's accuracy is 76% for actual agricultural points, and 89% for actual natural vegetation points [19] (Table 7)[20].

---

18 The points are not all simultaneously under cultivation because that would change the macro spatial price equilibrium.

19 These and subsequent predictive assessments exclude natural parks and private reserves. If we included these points and followed the rule that all such points are predicted to be under natural vegetation, the overall model's predictive performance would be much improved.

20 In contrast, use of a conventional 50% threshold dramatically reduces accuracy for cultivated points to 37%, and boosts accuracy for noncultivated only modestly, to 98%. Indeed one can trivially achieve an overall accuracy of 88.5% simply by predicting all points to be noncultivated. This illustrates the familiar statistical trade-off between type I and type II errors, and the arbitrariness of the 50% threshold.

Table 7 - Predicted vs. actual agricultural land use

	Prob(agric.) <.2	Prob(agric.) >.2	TOTAL
Actual natural vegetation	1591	198	1789
Actual agricultural use	56	176	232
TOTAL	1647	374	2021

The next table (Table 8) cross-tabulates actual land use against predicted use for semi-subsistence agriculture, again using a 20% probability threshold. What is particularly interesting is that of the 38 natural vegetation points incorrectly predicted to be in agriculture, 31% were secondary regrowth or thicket, indicating recent cultivation. By contrast, only 6.5% of the correctly predicted natural vegetation points were secondary regrowth or thicket. This further supports the assertion that low predicted probabilities of cultivation are useful for prediction. Note that the prediction criterion distinguishes sharply between commercial and semi-subsistence agriculture.

Table 8 - Actual land use vs. predicted probability of semi-subsistence agriculture

	Prob(semi-sub) < .2	Prob(semi-sub) > .2	TOTAL
Actual natural vegetation	1751	38	1789
Actual semi-subsistence	32	29	61
Actual sugarcane	64	0	64
Actual other commercial agriculture	103	4	107
TOTAL	1950	71	2021

Finally, the following table (Table 9) compares predictions for commercial cultivation with actual land use again using a 20% threshold. Predictions are highly accurate for points under sugarcane, less so for other commercial agriculture. Semi-subsistence and commercial agriculture are sharply distinguished. In fact, only one sample point had predicted use probabilities of more than 20% for both semi-subsistence and commercial farming.

Table 9 - Actual land use vs. predicted probability of commercial agriculture

	Prob(commercial agriculture) < .2	Prob(commercial agriculture) >.2	TOTAL
Actual natural vegetation	1661	128	1789
Actual semi-subsistence	54	7	61
Actual sugarcane	3	61	64
Actual other commercial agriculture	43	64	107
TOTAL	1761	260	2021

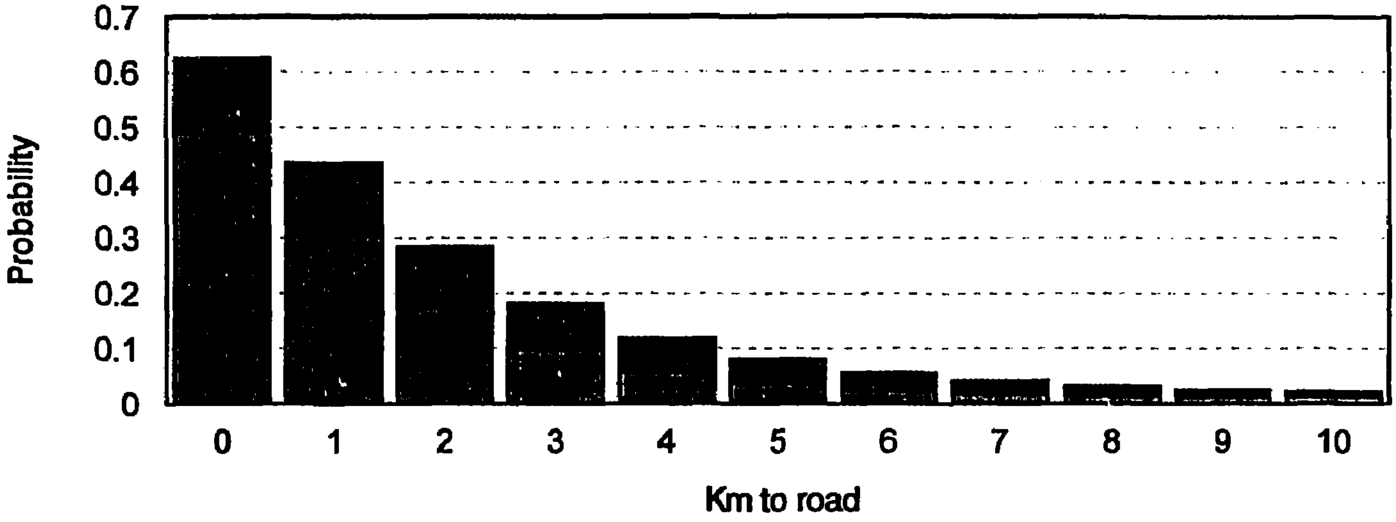
7.0 Discussion

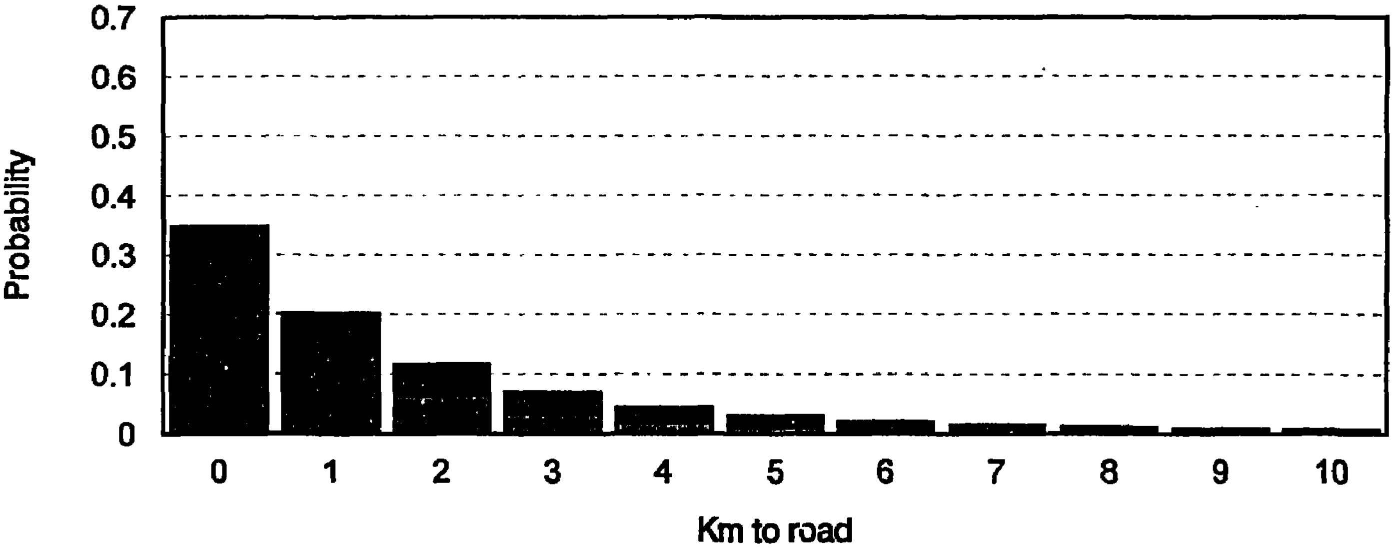
7.1 Implications for road-building

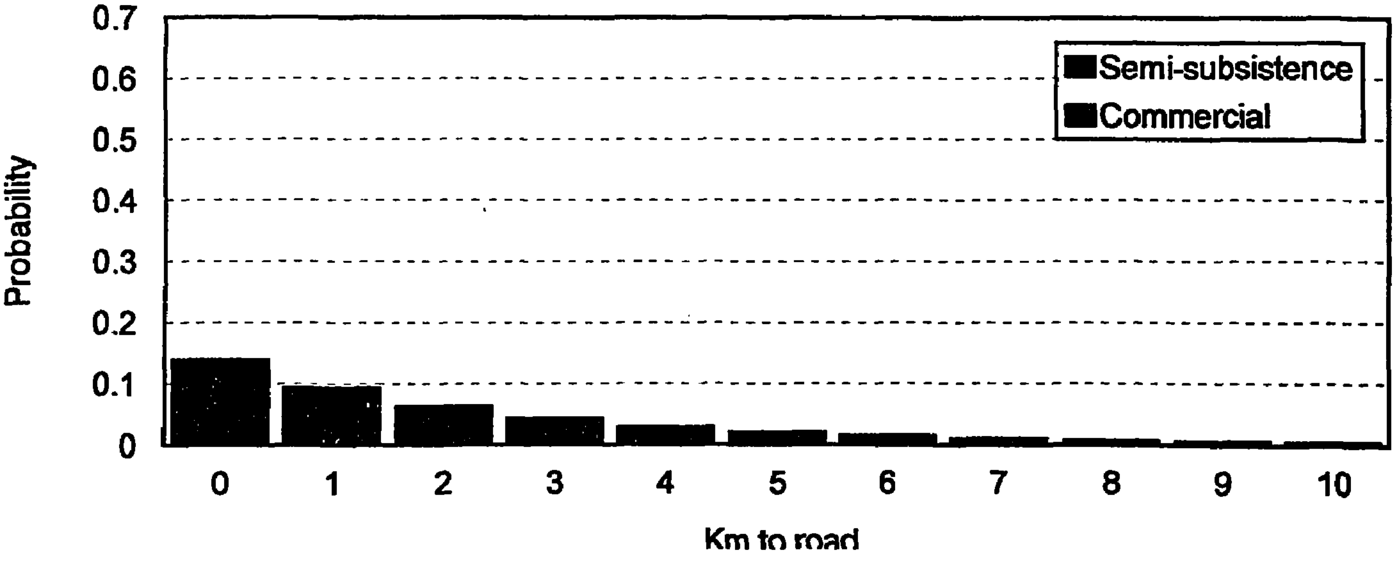
The results show that distance to road, on-road travel time to market, and agricultural suitability have a strong impact on land use and deforestation. These results are illustrated in Figures 3 and 4, which show predicted land use as a function of the three variables. Figure 3 describes land use on "agriculturally suitable" soils, here defined as not high slope, not low nitrogen, and sandy, with other soil variables set at the conditional mean. Spatial trend effects for both agricultural land uses are set at sample means. The three panels present predictions across two dimensions of distance to market: the distance to the road (horizontal axis of each panel) and the subsequent on-road distance to the nearest town (differentiated by panel). The top panel describes points which are close to town: the on-road travel time is just one minute. For points which are on the road (distance to road=0), there is a 62.4% probability of agricultural use, consisting of a 49.2%

Agriculturally suitable land

Figure 3


On-road time to town = 1 minute


On-road time to town = 20 minutes


On-road time to town = 100 minutes

probability of commercial agricultural use, and a 13.2% probability of semi-subsistence cultivation (in this, likely some form of truck farming.) As distance to road increases, the cultivation probability decreases, with commercial farming falling off more rapidly than subsistence farming. At 10 km from town, there is a 97.8% probability that the land is still under natural vegetation. The middle panel repeats the predictions for points sharing an on-road travel time of 20 minutes. The agricultural use probabilities are substantially reduced. The bottom panel describes points with an on-road travel time of 100 minutes. At this distance, the probability of commercial use is nearly zero; the land is more valuable for semi-subsistence farmers. Even for these farmers, the probability of cultivation falls off rapidly with distance from the road.

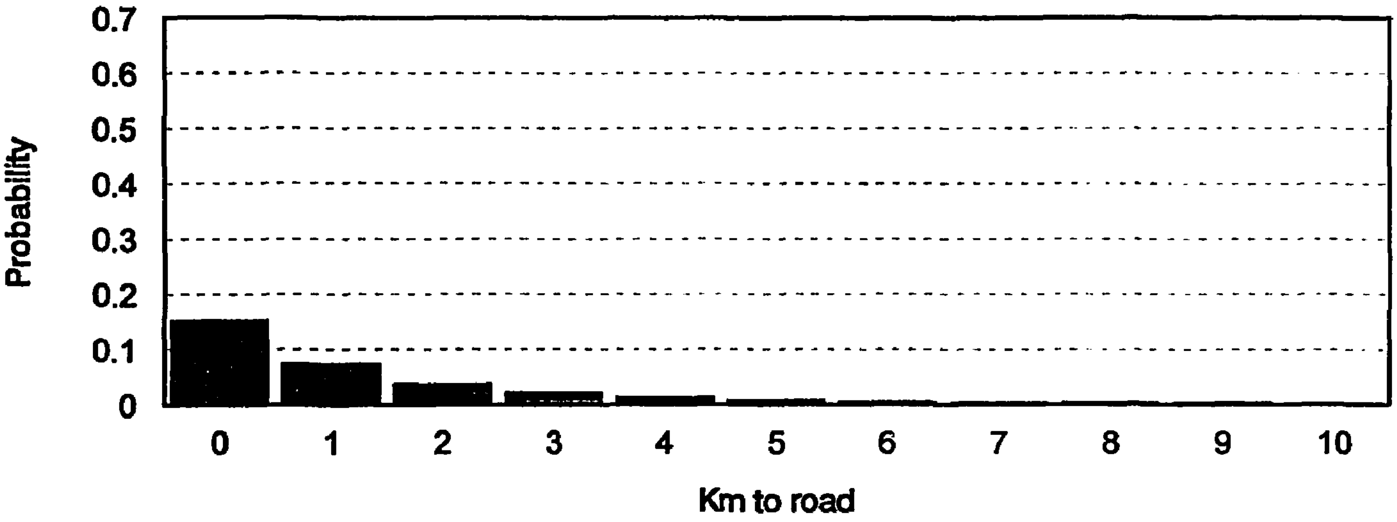
Figure 4 repeats the set of predictions for agriculturally marginal land, defined as being high slope and low nitrogen, with other variables set at their conditional means. The contrast with agriculturally suitable land is striking. Even close to town (top panel), the probability of agricultural use is just 15.2% at the road, dropping below 1% at 5 km from the road. At just 50 minutes (on-road) to town, the probability of agricultural use is only 1.2% at the road, dropping to 0.6% 1 km off the road. The dominance of commercial over semi-subsistence farming results from the latter's much stronger disutility for low-nitrogen soils. Clearly, though, these results are shaped by Belize's low population density.

With these estimates, we can begin at least indicatively to assess the costs and benefits of roads intensification vs extensification strategies. The top panel of Table 3 suggests high economic returns to increasing the density of roads in favorable areas near market centers. Building a feeder road to points which were formerly 2 km from the road system, for instance, boosts cultivation probability from 28.2% to 62.4%. The impact on labor demand and by extension on poverty depends on the particular crops and technology chosen. We have not modeled agricultural intensification here explicitly, but theory (see Appendix A) and experience suggests more land and labor-intensive agriculture nearer to town. The environmental impacts of such an intensification strategy will vary with the local circumstances, but in general we

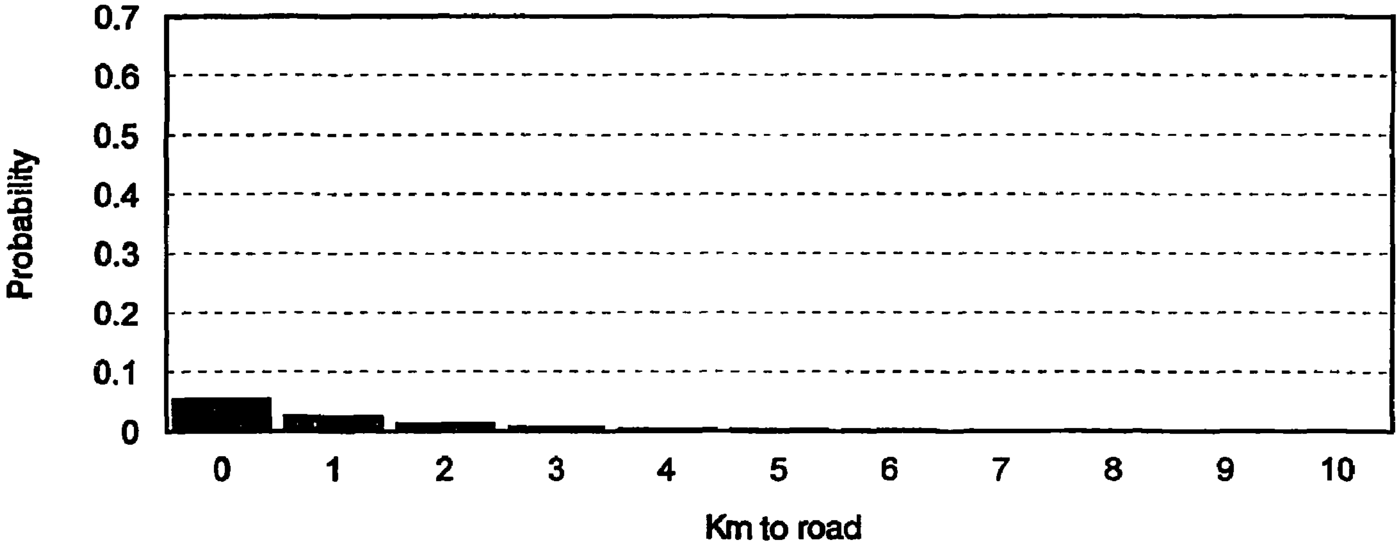
Marginal land

Figure 4

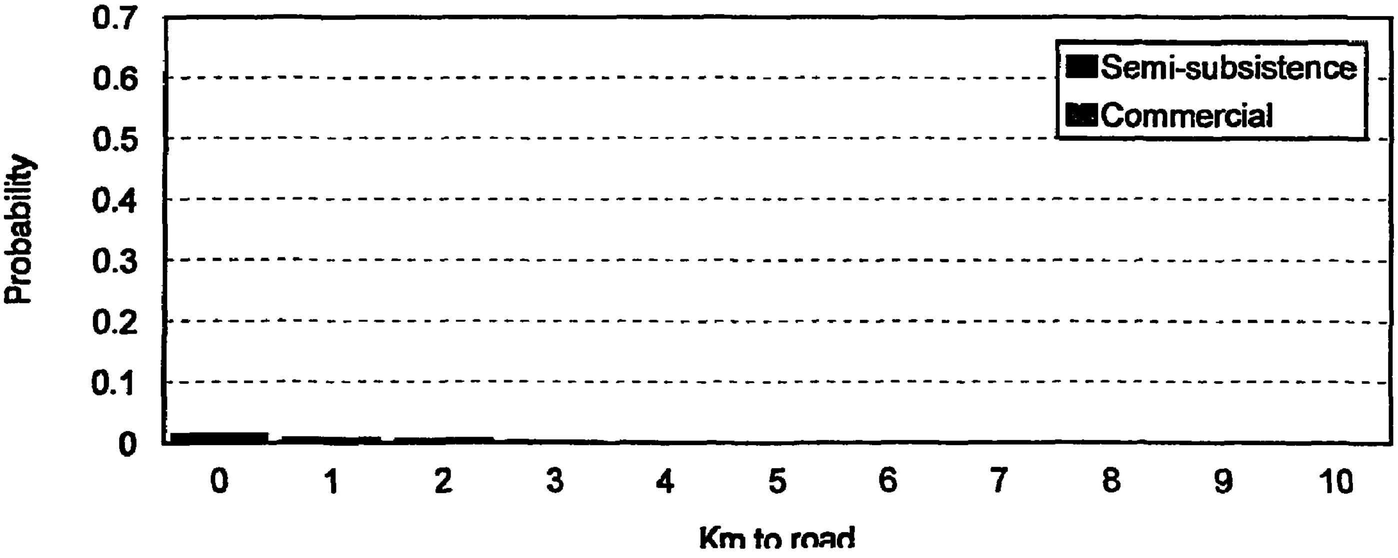
On-road time to town = 1 minute



On-road time to town = 20 minutes



On-road time to town = 50 minutes



would expect areas closer to town to have lower value for biodiversity conservation, simply because they are more disturbed and fragmented.

A contrasting, extensification strategy would push roads out to more remote areas. Newly opened areas with good soils would experience some forest conversion to semi-subsistence cultivation -- in this case, almost certainly milpa farming. Returns to labor and land would be relatively low. The environmental consequences might be substantial. Crop rotation would affect an area several times larger than that indicated by the current cultivation probabilities. Habitat fragmentation might result. If the roads were extended into remote areas with poor soils, there would be almost no economic gains to counterbalance the expenses of road-building. While there would also be little impact on forest cover, road access would expose the forest to various forms of degradation, such as overextraction of mahogany or poaching of birds.

We stress that this is only an indicative analysis. A more thorough analysis would involve calculation of the impacts of particular road-siting alternatives. It would also allow for general equilibrium effects: a substantial increase in cropped area would boost wages and reduce the price of domestically-consumed agricultural products, changing the coefficients embodied in the model. Finally, it would take into account distributional effects (across income groups or regions) of altered cultivation patterns.

7.2 Effectiveness of habitat protection

For conservation planning, it is useful to be able to assess the effectiveness of habitat protection. In the case of Belize, we observe very little cultivation in national parks and private reserves (about 0.3%). Is this because these areas are effectively policed, or is it because they are remote or otherwise unattractive for cultivation?

To address this question, we use the estimated coefficients to predict the extent of cultivation these areas would experience if they were not protected. Taking the expectation of predicted probabilities, 1.3% of the area would be predicted to be under current semi-subsistence cultivation, and 2.7% under commercial cultivation. Since the area affected by shifting cultivation could be five to ten times larger than that under cultivation at a given time, we conclude that habitat protection has been effective in Belize.

7.3 Effect of logging

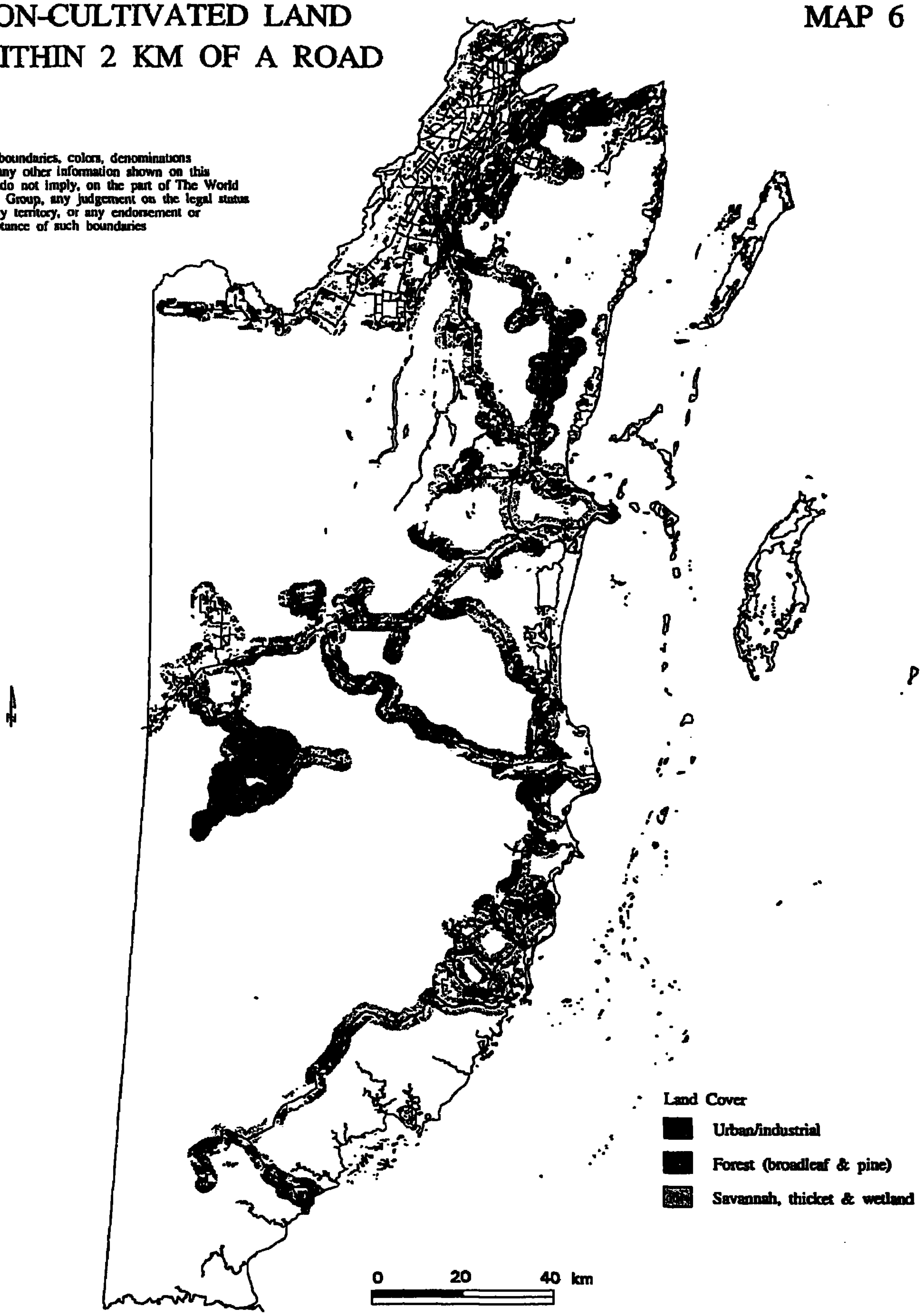
A striking finding is the predicted very low probability of agricultural use in areas which have poor soils and are far from markets -- even if they are close to roads. In fact it is easy to identify areas which are close to main roads but are not used for agriculture (see Map 6). This suggests that the hypothesis (often applied to Asia) that logging causes damage primarily by inducing follow-on migration does not necessarily apply to low-population density, remote, areas. In light of the results presented here, this suggests a more detailed examination, ideally using GIS data, of the dynamics of logging and deforestation in areas far from markets.

8.0 Summary and next steps

We have presented a static equilibrium model which relates observed land use to the relative returns to different alternatives. Relative returns at each point in the landscape are determined by road access, distance to market, and the inherent productivity of the land. The model was strongly supported by data from Belize. Market access and distance to road strongly affect the probability of cultivation; as hypothesized, the effect is stronger on commercial than on noncommercial agriculture. High slopes, poor drainage, and low soil fertility discourage both commercial and semi-subsistence agriculture. Semi-subsistence agriculture is found to be particularly sensitive to soil acidity and lack of nitrogen. This confirms anthropological studies which find that subsistence farmers are shrewd judges of soils. Taken together, these results suggest that intensification of the road network around market areas offers higher economic returns and lower environmental impacts than extensification of the road network into new areas.

NON-CULTIVATED LAND WITHIN 2 KM OF A ROAD

MAP 6



The boundaries, colors, denominations and any other information shown on this map do not imply, on the part of The World Bank Group, any judgement on the legal status of any territory, or any endorsement or acceptance of such boundaries

Land Cover

- ■ Urban/industrial
- ■ Forest (broadleaf & pine)
- ▨ Savannah, thicket & wetland

The model has a wide variety of shortcomings which we hope to correct in future work. First, it treats road siting as exogenous. Although data on agricultural suitability helps control for any resultant biases, we have suggested instrumental variables strategies to address this problem. Second, the assumptions underlying the multinomial logit specification are very strong; they will be relaxed via the use of multinomial probit or nested logit specifications. Third, the spatial trend variables currently explain much of the spatial variation in land use -- which is to say, the underlying causes have not been identified. We hope that incorporation of information on the spatial distribution of population will improve the model's explanatory power.

Two immediate extensions are planned. First, we will examine the ability of the model to predict land use changes over the period 1985-1994 in the Toledo District, the site of rapid recent immigration. Second, we will assess the potential impact of road network extensions on the environment, using data on the spatial distribution of species. Over the longer run, we would like to explicitly introduce spatial price formation into the model, so as to be able to explore the implications of changes in agricultural markets and policies.

Appendix A: Model derivation

Note: The equation numbers in this derivation parallel those in the non-technical presentation in the main body of the text.

Let P_{ik} be the price of the output of use k at point i, C_{ik} be a vector of prices of inputs to k at that point, X_{ik} be the optimal quantities of inputs for k per unit of land, Q_{ik} be the potential output of k at the point, and u_{ik} a random disturbance. The potential rent associated with devoting the point to use k is:

$$(1) \qquad R_{ik}=P_{ik}Q_{ik}(P_{ik},C_{ik})-C_{ik}X(P_{ik},C_{ik})+u_{ik}$$

P,C, and Q are endogenous, and in the current example unobserved. We derive a reduced from by specifying observable determinants of these variables. In the classic von Thünen interpretation, P and C are both strongly related to distance to market (or port or processing plant, depending on the commodity in question), reflecting transport costs. While a simple von Thünen model uses a linear function of distance, truncating when P=0, here it is more convenient to specify exponential functions:

$$(2) \qquad P_{ik}=exp[\gamma_{0k}+\gamma_{1k}D_{i}+\gamma_{2k}T_{i}]$$
$$C_{ik}=exp[\delta_{0k}+\delta_{1k}D_{i}+\delta_{i}T_{i}]$$

where D_i is the distance from point i to the road, T_i is on-road travel time to the nearest market, and the parameters are commodity-specific. (For a closer fit to a truncated linear function, polynomials in D and T can be added.) We hypothesize that output price decreases with both dimensions of distance ($\gamma_1>0$, $\gamma_2>0$), and that input costs increase with distance from market ($\delta_1>0$, $\delta_2>0$).

The production function, here expressed as output per unit of land, is assumed to be:

(3) $Q_{ik}=S_{ik}X_{ik}^{\beta k}$ $[0<\beta_k<1]$

The productivity factor S can be expressed as the product of agroclimatic and other variables s1, s2,... describing land characteristics:

$$S_{ik} = \lambda_{0k} S_{1i}^{\lambda_{1k}} S_{2i}^{\lambda_{2k}} \ldots$$

From (3), we can derive the demand for X:

$$(*) \qquad X = \left[\frac{C}{PS\beta}\right]^{1/[\beta-1]}$$

Substituting (3) and (*) into (1), suppressing the error term and the subscripts, and simplifying, we have:

$$R=PQ-CX=PSX^{\beta}-CX=X[PSX^{\beta-1}-C]=$$

(**) $C^{\beta/(\beta-1)}[PS\beta]^{1/(1-\beta)}(1-\beta)/\beta$

Together, (*) and (**) show that rent and input-intensity increase as output price increase, and decrease as input costs increase.

Substituting (2) and (3a) into (**), taking logs, reintroducing the commodity subscript and the stochastic term, and relabeling coefficients:

(4) $\ln R_{ik}=\alpha_{0k}+\alpha_{1k}\ln D_i+\alpha_{2k}\ln T_i+\alpha_{3k}\ln s_{1i}+\ldots+u_{ik} \equiv Z_i A_k+u_{ik}$

The coefficients on distance are predicted to be negative; those on productivity-enhancing land characteristics s are predicted to be positive. The magnitude of those coefficients will however differ markedly from crop to crop. For instance, transport costs are relatively high for sugar, yielding a large (negative) coefficient on the distance measures. By contrast, milpa farmers who produce mostly for subsistence may care relatively little about distance to market.

Point i is devoted to use k if:

$$(5) \qquad R_{ik} > R_{ij}, \quad \text{all } j \neq k$$

Returning now to the stochastic specification, if the disturbances u are Weibull distributed and uncorrelated across uses j, then this is equivalent to a multinomial logit model where the probability that plot i is devoted to use k is:

$$(6) \qquad P_{ik} = \frac{\exp(Z_i A_k)}{\sum_j \exp(Z_i A_j)}$$

(The coefficients of one use must be normalized to zero. Here forest is a natural choice for the default category.)

Appendix B: Instrumental variables approaches

Suppose that road siting is determined, in part, by indicators of agricultural development prospects. Suppose, further, that we lack information on those indicators. Then our estimates of the effect of road proximity on agricultural development will be biased, since proximity and development are co-determined by unobserved variables.

The instrumental variables solution is to find variables which are effective at explaining distance to the road or on-road travel time, but which are not correlated with agricultural development (after controlling for observable land characteristics). Auxiliary equations are then used to predict distance to road and on-road travel time as a function of exogenous variables. The predicted distance values are used in the main land-use equation estimates.

It is difficult to identify suitable instrumental variables. We tried an approach based on "virtual roads"[21] . The underlying premise is that the locations of major towns are exogenous, determined by geography and historical accident. We then argue that the location of the towns points predetermines the geometry, but not the precise routing, of the main intertown road network. In other words, transportation demand will inevitably create links between major centers, and those links are exogenous to the areas they traverse.

Road network geometry is used to generate instrumental variables as follows. Using GIS technology, we draw straightline virtual main roads between the seven market points, mimicking the actual primary road network. We then construct a virtual path linking any given sample point to the nearest location on the virtual road system. We can compute the mean slope and mean swampiness along this path. The length and characteristics of the virtual path, together with the on-virtual-road distance to the nearest town, are used as instruments for the actual on-road and off-road distance between sample point and nearest town.

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[21] This strategy was worked out with Peter Orazem.

In practice, we found that these instruments worked very well in explaining on-road travel time. In fact, straight-line distance between the sample point and the nearest town, by itself, had very strong explanatory power and was far simpler to calculate. Unfortunately, the instruments had little explanatory power for distance to the road. The resultant predicted values of distance to the road were highly collinear with other determinants of land use and therefore could not be used in the land use equation.

In future work, we will try an alternative approach. We hypothesize that distance to the road is a function of a point's accessibility, and of the agricultural suitability of nearby points. Holding constant the characteristics of a given point, it will tend to be farther from a road if it is in a mountainous area or in a swamp than if it is in a fertile plain. Thus we can construct instruments by computing the mean slope, elevation, swampiness, and agricultural suitability of the area within, say, a five kilometer radius of each point. (Note that the land use equation must then include not only distance from the road, but also mean slope and swampiness on the shortest path from point to road.) In the Belize context, the local density of mahogany and cedar trees is an additional, potentially important determinant of road construction, though data are not readily available.

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