CHAPTER 7 - Plant Invasions in an Agricultural Frontier: Linking Satellite, Ecological and Household Survey Data

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ABSTRACT

Bracken fern has become an important land transformation in the southern Yucatán peninsular region. The fourfold increase from 1985 to 2001 is associated directly with human disturbance, primarily agricultural activities. Once established, bracken fern's persistence is supported by fire, mostly incidental burns from the large amount of swidden fires set every year to clear farm and pasture lands. Its impacts include impediment of forest succession and farmland fallow, reduction in biotic diversity, and high labor costs to combat. This chapter examines the dynamics of bracken fern invasion by linking land-use history, satellite imagery, socio-economic and ecological data through the use of spatially-explicit models. The results of regional and parcel-level models show the importance of richer household survey data and less spatially aggregated socio-ecological data in order to predict the spatial distribution of bracken fern in the region.

INTRODUCTION

An important advance in land-use and land-cover change research is the development of spatially-explicit models aimed at understanding land conversion (Verburg et al. 2006; Veldkamp and Lambin 2001). The improvement in the understanding of the basic geographic and environmental processes associated with land cover change, and the progress in remotely sensed methodologies to characterize landscape have contributed to the advance of spatially-explicit models explaining and predicting processes of land transformation (Lambin and Geist, 2006; Turner, 2002). Land change models provide ways of linking land management decisions to land cover transformations and vice versa, thereby making such models useful at characterizing environmental feedbacks to human decisions, and changes in human behavior to biophysical changes (De Fries et al. 2005; Veldkamp and Lambin 2001).

Most land-change models have focused on understanding and predicting the process of deforestation due to its critical role in the global carbon and hydrological cycles, biodiversity loss, and land degradation more broadly (Foley et al., 2006; Watson et al. 2000). Models of deforestation have primarily focused on documenting the spatial scale and rates of change, and on the social dynamics stimulating forest loss, particularly land management practices. Minimal attention has been given to modeling different kinds of land transitions such as the role of plant invasions in land change (Mooney and Hobbs 2000). So far, models looking at plant invasions affecting the configurations of the landscape are rare (Schneider and Geoghegan 2006) and are mainly found in the ecological literature (Higgins and Richardson 1996; With 2002). Ecological models provide a framework where the spatial character of plant invasion is linked to the physical environment and the biological aspects of the invasive species. Due to the complexities of such relations, the human linkages are less explicit and only mediated through disturbance processes (e.g., fires, land clearance).

Changes in land use, land degradation and human disturbances provide opportunities for invasion, while invading species in turn can force changes in land use or modifications in management (Mooney and Hobbs 2000). Such processes represent a feedback to biophysical change that could be modeled using the spatially-explicit techniques developed by the land change research community. A challenge in modeling plant invasions then is the ability to incorporate social and ecological variables. These linkages can be tested through the spatial characterization of both land cover derived from remote sensing and land use through parcel-level data.

In southern Yucatán, Mexico studies have identified the role of a plant invasive, bracken fern (*Pteridium aquilinum* (L.) *Kuhn*) is an important element of the land-use and land-cover dynamics in the region (Figure 7.1). Bracken has increased fourfold in the area since 1985, impeding regular succession of the vegetation and affecting the spatial configuration of the areas under forest opened for cultivation (Schneider 2004). At first glimpse, bracken fern invasion seems to be the result of land degradation that creates an ecological niche into which bracken can expand. Current spatial configuration of bracken fern invasion in the region, however, suggest a more complex process involving land-use strategies and biophysical constrains (Schneider 2006). In order to understand the variables affecting bracken fern invasion in the region, an integrated approach linking the different socio-economic and ecological factors is required.

This chapter presents spatially-explicit models of bracken fern invasion in the southern peninsular region of Yucatán that integrate the process of biological invasion with biophysical and socio-economic variables. The models use a spatial dataset, which links together land-use history, satellite imagery, socio-economic and ecological data. The models are developed at both regional and local levels, and some of the challenges when using different scales of analysis are explored. The premise is that bracken fern invasion is an important land change in the region linked to environmental and land management practices, and requires an interdisciplinary framework that integrates the spatial character of the invasion to the understanding of the biophysical constraints and land management practices in the region (Schneider 2004).

Fig. 7.1. Bracken fern mixed with secondary forest in Southern Yucatán

SOUTHERN YUCATAN AND BRACKEN FERN INVASION

The study region is located at the frontier of the Mexican-Guatemalan border, an area of 22,000 km^2, which is home of the Calakmul Biosphere Reserve and is therefore considered a hot-spot of tropical deforestation (Figure 7.2) (Lepers et al., 2005). The southern Yucatán region contains the largest tract of continuous deciduous forest in Mexico and it is experiencing an annual rate of deforestation of 0.4 percent, comparable to other forest areas in Central America (Sader et al. 2005). During the Mayan Civilization, the region was intensively used for agriculture but after its collapse the forest returned (Turner 1987). Current forest composition reflects such land-use legacies (Lawrence et al. 2006). At the turn of the 20th Century, new migrants from other regions of Mexico arrived in the region to work mainly in cedar and mahogany logging industries. The increase in population and the ecological importance of the forest endow this region with a continuous conflict between the needs of the farmers and conservation goals.

Currently, the dominant land tenure system in the region is the *ejido.* This sector was created following the Mexican Revolution (1910-1917), a political and social upheaval with its roots in inequitable land distribution. Within *ejido* communities, land is communally regulated by an elected committee; but in this area of southern Mexico, *ejido* members (*ejidatarios)* typically enjoy usufruct access to a single parcel that is permanently allocated to their use.

The main activity of farmers is *milpa* cultivation, a polyculture system combining maize, squash and beans. Following semi-subsistence farming chili peppers are cultivated. They are a cash crop that has proven to be an important source of income for some *ejidos*. Households in the region are also diversifying their off-farm incomes. After cultivation, or during early stages of fallow, grasses are planted on some land parcels in the expectation of cattle ranching. Land clearance either for cultivation or for pasture is one of the main drivers of bracken invasion in the region (Schneider 2006).

Bracken fern invasion affects ecosystem recovery and household economics and it is considered an important part of land-use change in the region (Schneider, 2006; Lawrence et al, 2006). Bracken fern, *Pteridium aquilinum* (L.) Kuhn, has a cosmopolitan plant distribution. It is considered an invasive species because of its tendency to spread out of control, producing a monoculture that discourages the growth of other plant species, thus posing a direct threat to biological diversity (Figure 7.3).

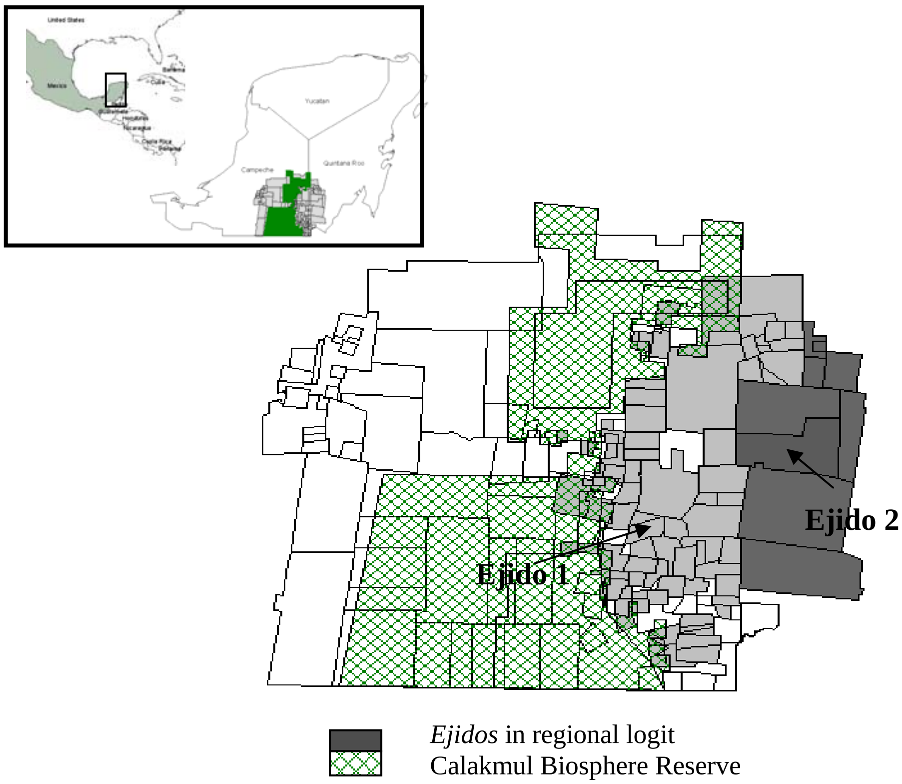

Fig 7.2. Map of study region. Areas in dark grey are the *ejidos* used for regional model. Parcel-level data was used to model bracken fern invasion for *Ejidos* 1 and 2

Bracken fern establishes itself on areas dominated by fires, deforestation, and agricultural activities (Page 1986; Pakeman et al. 1996), causing severe problems to both farmers and conservationists (Pakeman and Marrs 1996, Pakeman et al. 1996). The spread of bracken fern in Southern Yucatan is in part due to land clearance, fire regimes and land management practices (Schneider 2006). The increase of this invasive could potentially lead to further land abandonment and promote greater deforestation in the region (Schneider and Geoghegan- 2006). Thus, specifying where and why bracken fern invades, and why farmers decide to control it or not, are critical components of forest conservation and management in the region.

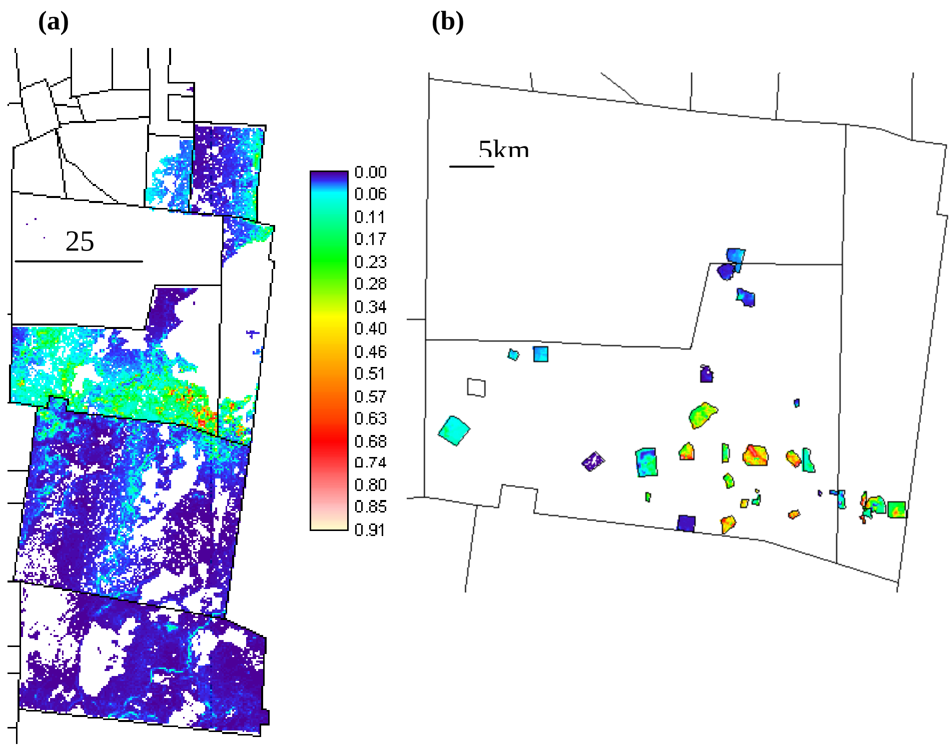

Fig 7.3 a. Probability of bracken invasion in the study region based on regional model estimations. **b**. Probability of bracken fern invasion using parcel-level socio-economic data

MODELS AND EXPLANATORY VARIABLES

The aims of the land change models presented in this chapter are to understand, through household surveys and census data, some of the dynamics that influence land managers' decisions whether to control bracken invasion and relate those decisions to biophysical constraints through the use remotely sensed data and geographic information systems. Similar approaches have been used to model deforestation in the region (Geoghegan et al. 2004).

Farmers are not directly invading their parcels with fern (as is the case with deliberately cutting forest for cultivation); however, the presence and increase of bracken fern is related to land management practices. As such, links between farmers' land practices and bracken fern invasion are needed to understand the invasion. The model developed in this chapter aims at evaluating such relations and estimating spatially the probability of bracken fern invasion in the region. Two approaches are taken to model bracken fern invasion in the region, one at a regional aggregated level, and the other at a parcel level. The main difference between these two approaches is the quality of the social data used. For the aggregated model, the social data are drawn from the Mexican censuses (from 1990 to 2000), while the parcel-level model employs social data developed directly form the land users for this study (Schneider 2006).

For both the regional and parcel-level approach, the logistic function was used. The logistic function calculates the probability of bracken fern invasion as a function of a set of explanatory variables. Using a spatial data set as the dependent variable allows for spatially-explicit results. The function is a monotonic curvilinear response bounded between zero and one, given by a logistic function of the form:

$$p = (y = 1 \mid X) = \frac{\exp(\sum BX)}{1 + \exp(\sum BX)}$$

where p is the probability of the dependent variable being 1; X is the independent variable (X_1, X_2… Xn); and B is the estimated parameter (B_0, B_1, B_2… Bn).

The logistic function can be transformed into a linear response with the transformation

$$p' = \log_e\left(\frac{p}{1-p}\right) \quad \text{hence} \quad p' = B_0 + B_1 X_1 + B_2 X_2 + B_3 X_3$$

The transformation from the curvilinear response to a linear function is called a logit, or logistic transformation. The logit transformation of dichotomous data ensures that the dependent variable of the regression is continuous, and that the new dependent variable (logit transformation of the probability) is unbounded. Furthermore, it ensures that the predicted probability will be continuous within the range from zero to one (Aldrich et al. 1984).

The dependent variable in each of the models developed in this section is the location and amount of change in bracken fern areas from 1985 to 2001.

The location of those areas was estimated using the land-cover maps created from processing Landsat Thematic Mapper (TM) from 1984-1996 and Enhanced Thematic Mapper (ETM+) for 1999 to 2001. Areas covered by bracken fern are structurally distinct from forest and other disturbed land covers in the southern Yucatan region, which allows them to be detected and differentiated in remote sensing analysis. Using principal components analysis and texture analysis it was possible to separate clearly the spectral signature of bracken fern from other land covers (Roy Chowdhury and Schneider 2004). Maps containing the following eight classes for each time period were created: upland forest, wetland forest, early secondary re-growth, late secondary re growth, agriculture, bracken fern, semi-inundated savannas, and water.

Binary maps of bracken fern-no bracken fern between 1985 and 2001 were created and cross-tabulated to estimate the changes in quantity and the location of bracken fern during that period. The classified maps described above are aggregated into bracken fern and other (including areas of upland forest, agriculture and secondary growth). Areas of lowland forest and inundated savannas are excluded because of the impossibility of these areas supporting bracken fern colonies. The resulting map, with zero indicating absence and one indicating presence, was used as the dependent variable for the models. For both the regional and parcel-level data, the model estimates the probability that a pixel that begins the time period of observation as *not bracken fern* will change into *fern* or will remain as *not fern*. In terms of land tenure, only *ejido* land is used in the model; private land and forest extensions from *ejidos* outside the region and the Calakmul Biosphere Reserve are excluded due to the lack of census data and the differences in tenure.

Explanatory variables

Two sets of explanatory variables are used in the models: biophysical and socioeconomic (Table 7.1). The variables included in the model were chosen looking at how land use might affect the invasion and how environmental variables could constrain or promote the spread of bracken fern in the region.

Table 7.1. Variables used in regional and parcel-level models of invasion

Data	Source	Description
Land cover data	Satellite data: Landsat TM and ETM+ (1987 to 2001)	7 land cover classes, including upland forest, lowland forest, secondary growth, agriculture, bracken fern, inundated savannas and water
Household survey data	Household surveys (n=46)	Demographic data (per household); Land use data, agricultural yields and fallow cycles; and Socio-economic data
Census data	INEGI, 1990 and 2000	Demographic data (per *ejido*); Access to basic services (percentage by *ejido*); and Socio-economic data (by *ejido*)
Ecological data	Digital elevation model, soils and climate from INEGI, 2000	Landscape metrics, slope, elevation and soil type

Data on demography, education, wealth and tenure were selected for the models due to their relationships to bracken fern invasion. Demographic data (population growth, age and gender) provides linkages to amount of land under agricultural production, labor and fern invasion in the land parcels. Population affects control for local demand for agricultural production, which could lead to different land uses (e.g., induced intensification) that constrain or promote the spread of bracken. Education can increase off-farm employment opportunities, thereby leading to an increase in bracken invasion due to land parcel abandonment. Higher levels of education and wealth can have two conflicting effects. On the one hand, wealthier and better educated communities are likely to have more off-farm opportunities, therefore decreasing agricultural activities and increasing the likelihood of invasion. On the other hand, if communities have more social capital, leading to access to subsidies and capital inputs, this could result in intensifying land use and controlling the spread of bracken fern.

The same biophysical explanatory variables are used for both the regional and the parcel-level models. One of the strengths of spatially-explicit modeling is the ability to use geographic information systems and remote sensing to create explanatory variables. Such variables capture the complexity of the landscape and other spatial configurations that affect the process of invasion. The variables included in the regional and parcel-level models for each pixel include: elevation, slope, aspect, fragmentation and soil type. Distance variables and landscape metrics are also included in the model: distance of each pixel to a forested area (zero if the pixel is a forest pixel) and distance of each pixel from paved and secondary roads. In the model, it is assumed that all pixels in each *ejido* have a potential for invasion (excluding seasonal wetlands and areas not considered *ejidos*). The distance of each pixel from the nearest bracken fern pixel was estimated through a map layer that calculated the total number of bracken fern pixels in a 5 x 5 window. It is assumed that the closer to a large area of bracken fern a pixel is, the greater the likelihood of it being invaded.

Socio-economic variables for aggregated regional model

Census data at the *ejido* level is the source for socio-economic data for the aggregated model. The census data used in the model ranges from 1990 to 2000 (INEGI 1990, 2001). The demographic variables used for the regional model were: total population and total number of women and men in each *ejido*. Two variables that include the change in male and female population during this period were also included. Proxy data for wealth are percentage of population with water, sewerage and electricity. Data on education included are percentage of the population that know how to read and write, and the population older than 15 that has attended post-elementary school.

Socio-economic variables for parcel-level model

The sources of the socio-economic data used for the parcel-level model are the surveys developed for this study. A total of 46 (15 for *Ejido 1* and 31 for *Ejido 2*) farmers were interviewed and the parcels were geo-referenced with the use of geographic positioning system (GPS). During each farmer interview, the parcel was walked through and reference points were taken around cultivated plots and boundaries of the parcel. Special GPS points were taken in areas with bracken fern and used to develop training sites for the Landsat TM/ETM+ classification. The results of the visits were a sketch map for each farmer interviewed (Figure 7.3). The spatially-explicit variables developed through GIS and remote sensing were then linked to the parcel through the sketch maps.

Household-level demographic data gathered from the survey included the number of men and women older than 11, and the total number of children under 11. Disaggregating the information by age and gender provides ways to link data on labor and fern invasion in the parcels. Education variables include the education level of the household head as well as the number of household members with more than eight years of education. Because of data limitations, potential wealth and physical capital are included through the percentage of households that have access to basic services and middle and high-school education.

Variables defining land tenure characteristics are also included in the parcel-level model. The number of years a farmer has been an *ejidatario* and number of years working in the same parcel provides a proxy to the tenure aspects of each parcel. The *ejido* members set the amount of land assigned to each farmer when the *ejido* is founded; the locations of cultivation inside the *ejido*, however, could vary through time. Farmers usually cultivated only the area upon which the *ejidatarios* and the members of the community agreed at the time the *ejido* was founded. *Ejidatarios* vary rarely changes parcels.

In summary, in both models the biophysical and distance variables are the same: slope, aspect, elevation, soils, rainfall, distance of each pixel from primary forest, number of bracken fern pixels in a 5 x 5 window, size of the *ejido*, pixels belonging to a forest extension and distance of each pixel from paved and secondary roads. The socio-economic data for the regional model aggregated at the *ejido* level (Figure 7.1) drawn from the census includes: total population in 1990, total female and male population in 1990, number of residents with access to piped water and electricity and the number of people older than 15 with more than elementary school education. For the parcel-level, the socio-economic data comes from a household survey and it includes: the numbers of males and females older than 11, the number of children, the number of years the head of the household was at school, the number of years as *ejidatario*, the number of years working in the parcel visited and vehicle ownership by a household member.

REGIONAL AGGREGATED MODEL

The regional aggregated model was estimated for the eastern part of the southern Yucatán peninsular region using a logit function explained above. This sub-region extends from the Calakmul Biosphere Reserve eastward. The eastern section has larger areas invaded and it was the focus of much of the fieldwork underpinning this research. Table 7.2 shows the main land cover transitions occurred in the sub-region between 1985 and 2001 and it shows how the increase in bracken fern areas is larger than the increase in areas used for agricultural production.

The estimated coefficients and statistical significance of each of the variables used in the model are shown in Table 7.3. Figure 7.2(a) shows the probability of bracken fern invasion based on the model estimations. Due to collinearity among the census data variables, a few variables mentioned in the previous section were dropped from the analysis. The signs of the coefficients are interpreted given the statistical significance as follows: a positive coefficient means an increase in the probability of bracken fern invasion and a negative sign a decrease in the probability.

Table 7.2. Land cover estimates for the southern Yucatán peninsular region (nine *ejidos*: total area: 2,138 km^2)

Year	Bracken fern	Agriculture	Secondary vegetation	Lowland forest	Upland forest
1985	15.8	93.2	203.7	434.6	1391.0
1994	40.1	90.4	187.2	421.9	1420.0
2001	75.0	67.9	190.8	416.1	1389.0

All socio-economic variables resulted in a negative correlation with bracken fern invasion. In terms of demographics, an increase in the population will decrease the probability of bracken fern invasion. Change in total population from 1985 to 1990 and the total number of men in the population has a negative relation with the invasion. The result supports the hypothesis that increasing land pressures provide an incentive to combat the spread of the fern and a larger labor force provides the strength to do it through weeding.

Positive correlations exist between some of the biophysical variables and the invasion. The greater the slope angle, the higher the probability of invasion; this results reflects the inability of the species to grow in seasonally inundated terrain which, in this area, has low gradients. Parcels with steeper slopes are not usually suitable for agriculture therefore farmers would not spend time removing bracken. The invasion by bracken of steep slope areas is most likely driven by fires originated in areas nearby.. The relationship between rainfall and soils and bracken is positive. The former reflects the preference by farmers for rendzinas for agricultural purposes. Once vegetation is cleared the first step to facilitate the invasion has been taken.

The spatially-explicit variables show some interesting results. First, a longer distance from forest and a more fragmented landscape are positively correlated with bracken fern invasion, indicating how cleared land is preferred by bracken for establishment and spread. Distance variables and the fragmentation index suggest that an area surrounded by and in close proximity to forest withstands bracken fern invasion better than other areas, either owing to the nearby repository of plant species that could compete with bracken fern invasion or to the protection from fire afforded by the forest. Areas close to roads have higher probabilities of invasion, in part because incidental fires commonly burn along roadsides. Forest extension land has a lower probability of invasion, an expected result given that land is protected from being cleared in the extension zone.

Table 7.3. Estimated coefficients and standard errors from the regional logit model

Dependent Variable: Bracken invasion or no invasion	**Estimated coefficient**	**Standard error**	**t - statistic**
Socio-economic			
Forest Extension (0,1)	-4.935	0.08649	-57.06
Total population (per *ejido*)	-0.0107	0.00128	-8.33
Change in total population from 1990 to 2000 (per *ejido*)	-0.0024	0.00039	-6.16
Change in male population from 1990 to 2000 (per *ejido*)	-0.0030	0.00039	-7.71
Literate population (per *ejido*)	0.0603	0.00422	14.29
Higher education (per *ejido*)	-0.0289	0.00133	-21.75
Ejido size (# pixels, hundreds)	-1.7e-05	3.89e-07	-45.77
Distance			
Distance to road (m)	-0.00024	2.04e-06	-118.40
Distance to nearest primary forest (m)	0.00462	0.00003	142.35
Biophysical			
Fragmentation index (0,1)	2.60080	0.04364	59.59
Soils	0.71361	0.02055	34.71
Elevation (m.a.s.l.)	-0.00388	0.00020	-19.27
Rainfall (mm/yr)	0.00292	0.00011	26.43
Aspect (0 to 360^o)	-0.00030	0.00004	-7.90

Slope (degrees)	0.12851	0.00140	91.43
Number agricultural pixels (5x5)	-0.08285	0.00221	-37.37
Constant	-4.19483	0.16181	-25.92
Pseudo R^2	0.2213		
Number of observations	2,415,730		

The spatial predictions showing the probability of invasion are shown in Figure 7.3 (a). The best way to evaluate how good the predictions are is to compare them with the actual event. There is not a clear way to compare predicted values with actual values; however, in the actual event land is either invaded or not, and the predicted value represents a probability value. The prediction is a probability of change, while the actual is discrete--either the pixel changes or not. To move the probability to a prediction, a critical value is chosen and values at either side of it determine the result.

A two-fold approach is taken here to assign the critical value. The actual amount of invasion is calculated using the remotely sensed data; then the spatial distribution of higher probability pixels are sequentially identified until the actual amount has been selected. Using IDRISI Kilimanjaro GIS software, the probability image from the logit model was ranked. The highest ranking pixels were selected and assigned as predicted fern. The critical value for selecting the areas predicted as invaded in the model was 0.28.[1]

The models do not attempt to predict the actual amount of the bracken fern invasion in the region. Taking the amount as given, the model predicts the spatial distribution of the area invaded over the landscape. A map of the areas selected by the model to be invaded (predicted bracken invasion) is then compared to the map of areas that have actually been invaded by bracken fern during the period of 1985/87 to 2001.

Figure 7.3 shows the probability map of invasion for the eastern part of the region, and Figure 7.4 shows the results of spatial cross-tabulation. Of the pixels that were predicted to be fern, 34 percent were actually fern and only 2 percent of the pixels predicted as fern were actually non-fern (Table 7.6). The fact that most of the area in the model is non-fern enhances the accuracy to predict correctly the pixels kept as non-fern. Even though less than half of the pixels were predicted correctly as fern, it is important to notice that the mistakes are usually clustered in space and close to the correctly predicted, invaded areas.

[1] Critical values used for models are usually 0.5, meaning that probabilities of 0.5 or higher will be usually chosen to predict an event.

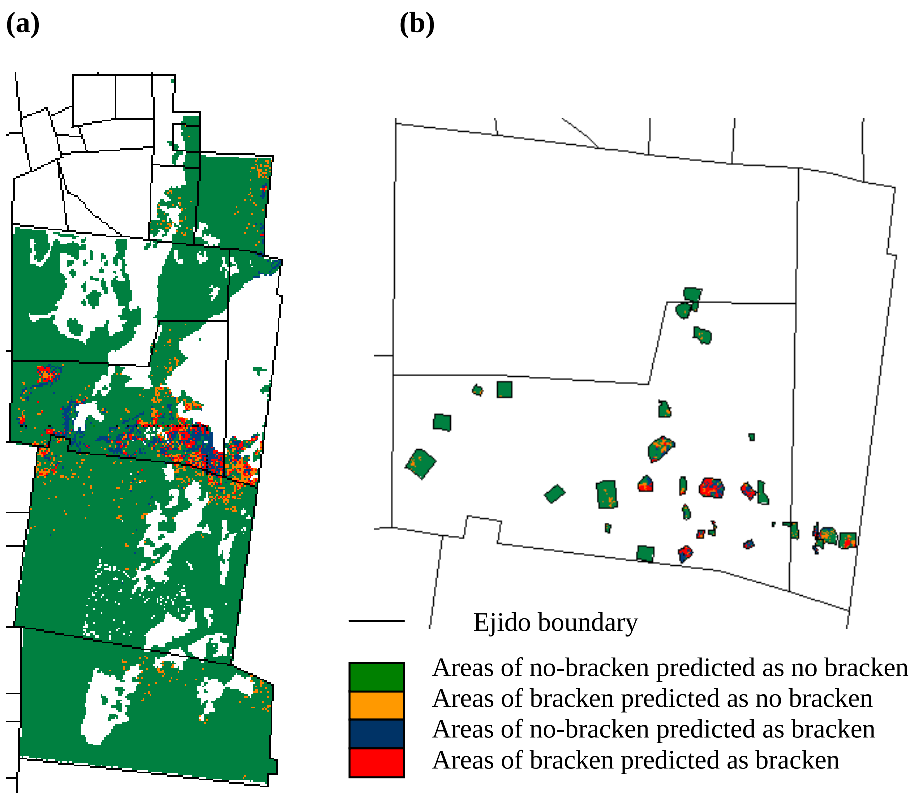

Fig 7.4. a. Results of spatial cross-tabulation between predicted values from regional model and actual areas cover by bracken fern in 2001**. b.** Cross tabulation for *Ejido* 1 using the predicted-values from parcel-level data.

The poor results obtained in predicting the spatial location of invasion could be attributed to the level of aggregation, mainly for the socio-economic variables. The variables used as proxies of demographics and wealth are less successful in capturing a very diverse range of land-use management strategies and histories that exist in the region. Models of deforestation in the region using similar data sets also show low levels of prediction. A regional model of deforestation correctly predicts 33 percent of the deforested pixels; for the pixels that remain forested, the regional model correctly predicts 96 percent of those pixels (Geoghegan et al. 2004).

Table 7.6. Results of Ordered Least Square regression model at parcel level.

	EJIDO 1		*EJIDO* 2	
Dependent variable: percent change in bracken	Estimated coefficient	Prob>|t|	Estimated coefficient	Prob>|t|
Socio-economic (varies by household (hh))				
Number of men > 11 (per hh)	0.158	0.058	-0.039	0.023
Number of children <12 (per hh)	-0.060	0.149		
Education of household head in years (per hh)	-0.107	0.043	-0.026	0.006
Number of years since arrived (years)	0.009	0.305*	-0.006	0.022
Working days per weeding (per hh)	-0.014	0.060		
Distance and landscape (varies by hh)				
Distance from household to plot (per pixel) (km^2)	-0.016	0.062	-0.038	0.003
Distance from parcel to nearest road (per pixel) (km^2)	-3.5E-05	0.07		
Distance from parcel to primary forest	0.001	0.039	-0.002	0.014
Biophysical (varies by hh)				
Upland soil (0,1)	0.685	0.05		
Slope (degrees)	0.092	0.053		
Elevation (m.a.s.l.)			0.001	
Constant	-0.380	0.351		0.399*
Number of observations	31		15	
F (10, 20)	3.24		(6,8)11.50	
Prob > F	0.0121		0.0015	
R^2	0.6185		0.8961	

PARCEL-LEVEL MODEL

A logit model and ordered least square (OLS) multivariate regression were estimated at the parcel level. The results of the logit model are used in this chapter to compare modeling approaches at different scales of analysis: parcel-level and regional model (or aggregated model). The OLS approach provides ways that compare the relationships between explanatory variables and bracken fern spread among *ejidos* with contrasting land management practices. Such comparison is difficult with a regional approach because the *ejido* level data is aggregated.

The dependent variable in the logit model is the same as in the aggregated model: pixels in the parcels that change into bracken or not from 1985 to 2001, the unit of observation being the pixel. The differences in the parcel-level model are in the independent variables, which come from the household surveys. For the OLS regression model, the dependent variable is the percentage change in amount of area under bracken fern from 1985 to 2001 in each parcel surveyed, the unit of observation in this case being the number of parcels (*Ejido* 1 = 15, *Ejido* 2 = 31).

The results of OLS are not spatially explicit, but allow testing different statements regarding land management practices and bracken invasion. Examples of the statements are: bracken fern invasions are more severe where larger plots or many contiguous plots have been cleared and burned frequently. Bracken fern is most successful in areas where farmers have sufficient land such that they can afford to lose agricultural plots to the invasive. Farmers who are land constrained are more likely to manage the invasion in order to minimize the spread of the fern.

For spatially-explicit results a logit regression was estimated using the pixels in each parcel as the dependent variables. Using the same set of variables as the regional model, the logit model estimates the probability of a pixel being invaded and the results are presented in a spatially-explicit manner (Figure 2b). For the OLS and logit models, calculations were made to evaluate if the explanatory variables were statistically significant. The larger number of observations of the logit model resulted in all explanatory variables being statistically significant in contrast with the regression model where just few were (Tables 7.4 and 7.5).

Table 7.4 Results of logit model at the parcel level for *Ejido* 2

Dependent variable: bracken or not bracken	Estimated coefficient	Standard error	t -statistic
Socio-economic (varies by household (hh), n=31)			
Number of men > 11 (per hh)	0.878	0.384	22.87
Number of children < 12 (per hh)	-0.134	0.013	-10.21
Education of household head in years (per hh)	-0.261	0.023	-11.33
Number of years since arrived (years)	0.027	0.002	9.29
Number of years worked on the same parcel (per hh)	-0.029	0.002	-10.18
Distance and landscape (varies by pixel)			
Distance from household to plot (per pixel) (km^2)	-0.055	0.036	-15.27
Distance from parcel to nearest road (per pixel) (km^2)	-0.0001	9.39e-06	-17.63
Distance from parcel to primary forest	0.003	0.0001	17.03
Biophysical (varies by pixel)			
Soil	1.652	0.118	13.93
Slope (degrees)	0.076	0.007	10.88
Constant	-4.151	0.166	-24.93
Number of observations	5164		
Pseudo R^2	0.1719		

In terms of spatial predictions at the parcel level, the same method used for selecting pixels in the aggregated model was used to choose the pixels more likely to be invaded from the logit model. The maps of probability and validation for *Ejido* 2 are shown in Figure 7.3, and Table 7.5 shows the results of the cross-tabulation between the predicted and actual areas of bracken fern for *Ejido* 2: 54 percent of the pixels predicted as invaded were actually invaded, and 11 percent of the pixels that were predicted to be bracken were actually not invaded. The critical point for pixel selection was 0.34, higher than in the aggregated model, illustrating the impact of improved scalar congruency in the data.

The fact that at the parcel-level socio economic information is better captured could indicate the improvement of the results over the regional aggregated approach. In terms of prediction, this model seems to represent better the patterns of invasion at the parcel level. A larger sample would improve the results of the models making it possible to include a larger number of explanatory variables that could be evaluated.

Table 7.5. Cross-tabulation of actual with and without bracken fern (2001) and areas predicted by the regional and parcel-level logit models

Regional Model	Actual area without bracken (km^2)	Actual area with bracken (km^2)	Total
Predicted area without bracken	1502.6	45.90	1548.5
Predicted area with bracken	45.9	23.86	69.76
Total	1548.5	69.76	1618.3
Parcel-level Model			
Predicted area without bracken	17.14	2.15	19.29
Predicted area with bracken	2.15	2.49	4.64
Total	19.29	4.64	23.93

There are several demographic and economic differences between the two *ejidos* used to estimate the OLS regression. The first is the fact that bracken fern density is larger in *Ejido* 2 than in *Ejido* 1. A larger number of children and men older than 11 reside in *Ejido* 1 than *Ejido* 2, and a slightly greater number of women per household live in *Ejido* 2 than in *Ejido* 1. The average number of years of education of the heads of the households are higher in *Ejido* 2 than in *Ejido* 1. The average years in tenure are longer in *Ejido*2—almost double the years of the farmers in *Ejido*1. Distance measurements indicate that cultivated plots in *Ejido* 2 are closer to farmers' houses than in *Ejido*1 (In *Ejido* 1 farmers are at least 10 times farther away from their plots than farmers in *Ejido* 2). Also parcels in *Ejido* 1 are closer to forested areas than in *Ejido* 2. Distance to roads in both *ejidos* is similar, however. Yields for the year 2000-2001 in *Ejido* 1 are lower than in *Ejido* 2, where weeding is more frequent. Elevations are higher and slopes greater in *Ejido* 1, and annual average rainfall is slightly higher in *Ejido* 2. Overall, *Ejido* 2 has a larger population but a smaller number of children than *Ejido* 1; as in much older *Ejido* 2, established as a forestry effort, land holdings are larger and land has been used longer compared to *Ejido* 1.

The total number of independent variables used for the OLS regression are less than that used for the logit model because of the sample size (in order to have enough degrees of freedom for the statistical estimations). The variables were chosen for the model as follows: two independent regressions were estimated, one only with socio-economic variables and the other with biophysical-distances variables. Only statistically significant variables were retained. For *Ejido 1*, a total of six independent variables were included in the model, and for *Ejido 2* a total of 10 (Table 7.6). From the household survey these were: the number of men older than 11, the number of children (younger than 11), the number of family members with high school education, the number of years they have lived in the area, the number of years working in the parcel surveyed, and the distances of the parcels from roads and their houses. The biophysical variables used were slope angle, soil type and distance from primary forest. The distance measures were the same those used in the regional model, with the addition the distance between the parcel and their houses in the villages.[2] The results of the OLS regression (Table 7,6) show the relationship between the increase in bracken and socio-economic characteristics. The calculations were made to evaluate if the explanatory variables are statistically significant and how they differ by *ejido*.

The regression model estimations presented here allow the selection of statistically significant variables. First, interpretation of the relationship between the explanatory variables and bracken fern invasion are discussed for *Ejido* 2. All the demographic variables included in the model with the exception of time of arrival in the *ejido* were statistically significant. An increase in percentage of bracken change with the increase in the number of men older than 11 per household and (the not statistically significant) the longer a head of household has lived in the region. A decrease in the amount of bracken fern in a parcel occurs with an increase in the number of children, the number of years of education of the head of household and greater the number of years they have worked the same parcel. The probability of invasion is less if parcels are farther away from roads; but is increases if parcels are farther way from primary forest, the parcels are located on rendzinas and the slopes are steeper.

[2] In both *ejidos* the area assigned to each *ejidatario* was set at the time the *ejido* was founded. For *Ejido* 2 each farmer has access to 100 ha; in *Ejido* 1 only 40 ha. The size of the plots worked at the time of the survey visit varied among *ejidatarios*, however.

Some of the results are consistent with expectations. Families later on in their lifecycle and residency tend to have a large set of parcels and can afford to lose some to invasion. However, those earlier in the lifecycle tend to work longer to control the spread of bracken. Parcels close to roads are usually cleared and accidentally burned more, which leads the fern colonies to establish and spread. Cleared areas distant from forest are also more vulnerable to fires and the colonization of secondary vegetation more difficult as the repositories of forest species are further away. The *a priori* expectation on the education variables is that greater education increases the off-farm employment opportunities, thereby leading to an increase in the presence of bracken due to the abandonment of land.

A counter intuitive result, perhaps, is the positive relationship between the number of men in a household and fern invasion in *Ejido 2*. Characteristics of land management in the region show that extra labor for weeding and cutting results in better control of the spread of bracken; consequently, having more men in the household helping in those activities should result in better control of bracken fern. The result found may reflect the lifecycle issue noted above and the fact that the older households in *Ejido 2* tend to have surplus land and may be moving from farming into off-farm activities (e.g., services).

The results of the regression model for *Ejido 1* are a bit different from *Ejido* 2 (Table 7.6). None of the biophysical variables were statistically significant.[3] The most interesting difference is a negative relationship that exists between number of men older than in a household and fern invasion. *Ejidatarios* in this *ejido* have less land and are more dependent on farming activities for their income than *ejidatarios* in *Ejido* 2. The contrasting results indicate that labor availability operates in connection with the orientation of the household economy.

COMPARING LOCAL VERSUS REGIONAL MODELS OF BRACKEN FERN INVASION

The difference in probabilities between the regional-census logit model and the parcel-level logit could be considered a measure of the improved fit of the

[3] Elevation was statistically significant in the regression when only biophysical variables were included. For this reason, elevation was included in the final regression model.

household model, given the higher cut-off probability. For the aggregated model, the critical point was 28 percent and for parcel-level model, 35 percent. Another way to evaluate the relative fits of the models is to compare the total number of correct and incorrect predictions. The regional logit model correctly predicts 34 percent of the invaded pixels, while the parcel level correctly predicts 54 percent of the pixels affected by bracken invasion. For the pixels that remain as forest, the regional logit model correctly predicts 97 percent of those pixels, while the parcel level correctly predicts 89 percent of those pixels.

The improvement of the parcel-level model for predicting invasion reflects the value of adding the richer household level survey data that better captures the individual causes of invasion than is possible at the aggregate level with the census data in the regional model. An additional possible reason for the better predictions of pixels that remain forest for the regional logit model over the parcel model is that for the latter the agricultural plot boundaries for the individual household are known from the sketch maps associated with the household survey. For the regional model, however, only the boundaries of each *ejido* are known, not the boundaries of the potential agricultural land within each *ejido*. As much *ejido* land is designated as communal forest and is therefore ostensibly off limits for cultivation; the model coincidentally achieves a relatively high accuracy in correctly predicting such land not to be invaded.

As with other attempts to model land-use and land-cover change, there remains much data to be collected and much modeling to be done to capture the variation and dynamics of the invasion in the region. As previously discussed, less aggregated socio-economic data, e.g. information on the location of within-*ejido* settlement, would likely improve the accuracy of the regional model. Further modeling work includes adding more temporal observations to the models and, for the parcel-level model, an increase in the number of parcels included could help in such improvements.

CONCLUSION

The human-environment dynamics that give rise to invasive species are an important element of landscape dynamics, with consequences ranging from impacts on biodiversity to net primary productivity and human use values. For the most part, research on plant invasions has examined these plant species in terms of the biophysical dimensions alone with only modest links to the human dimensions. Importantly, the spatial dimensions of invasion are not necessarily a component of their analysis. This chapter provides an example of how socio-economic data at different levels of aggregation, ecological and remotely sensed data could elucidate the dynamics of plant invasions through the use of spatial explicit models.

The models combine different types of spatial data and different levels of spatial aggregation. Some of the dynamics of bracken fern invasion and the variations of spatial patterns are understood through spatially-explicit models that move beyond modeling the magnitude of changes within a region to modeling the locations of that change.

Biophysical and spatial data hint that certain environmental aspects (e.g., aspect, fire frequencies and concentration of limiting nutrients create differences in susceptibility to bracken establishment, and repeated burning of fern-dominated areas favors its retention. Socio-economic and spatial data, however, indicate that the willingness of farmers to combat bracken fern invasion is related to the land, labor, and capital conditions of the farm household. Characterization of a spatially-explicit physical environment and land-use practices result in understanding current process of disturbance and resource distribution in the region which contribute to the spread of bracken and determine its current pattern.

One of the applications of such models is the ability to forecast trajectories of invasion, which are difficult to assess due to the complex and unpredictable nature of the relations among environmental responses and the changing political and social conditions of the systems affected by plant invasions. Plant invasion could be better understood if models could estimate the relative roles of land-use strategies and ecological responses.

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