Land Abandonment in an Agricultural Frontier After a Plant Invasion: The Case of Bracken Fern in Southern Yucatán, Mexico

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Plant invasions and their impact on land use pose difficult research questions, due to the complex relationships between the ecological nature of the invasion and the human responses to the invasion. This paper focuses on the linkages between an invasion of bracken fern and land use decisions in an agricultural frontier in southern Mexico. Agriculture in this region is practiced on an extensive basis, using traditional slash-and-burn techniques of temporary cultivation and continuous rotation through forest fallow. We investigate the factors that affect the decision of a subsistence farmer to either continue cultivating an invaded agricultural plot or permanently abandon the plot and cultivate elsewhere. We develop an agricultural household model of land use choices, where households maximize utility subject to constraints on land, labor, and income. We subsequently test the hypotheses raised, using data from a small household survey performed in the region in 2002.

Key Words: bracken fern invasion, land abandonment, agricultural household model, Mexico

Invasive species propagation is a significant global change phenomenon that affects biological diversity, ecosystem function, and human welfare (Vitousek 1994, Vitousek et al. 1997, Mooney and Hobbs 2000, Pimentel et al. 2002). Plant invasions and their impact on land use pose difficult research questions, due to the complex relationships between the ecological nature of the invasion and the human responses to the invasion (Hobbs 2000, McNeely 2001). The general assumption in the ecological literature is that human disturbances and land degradation promote plant invasions (Suazo 1998, D'Antonio and Kark 2002), but little research has addressed the roles of different land use strategies in response to plant invasions. The research in this paper focuses on the linkages between a plant invasion and land use decisions in an agricultural frontier in southern Mexico.

In this region of southern Mexico, during the past 20 years there has been a fourfold increase in the area covered by bracken fern [*Pteridium Aquilinium* (L.) Kuhn]. Bracken fern has become an invasive species globally, under a wide range of environmental conditions (Schneider 2004). Most of the agriculture in this region is subsistent and known locally as *milpa,* a centuries-old form of Maya agriculture dominated by maize and typically intercropped with beans and squash (Turner 1983). Agriculture is practiced on an extensive basis, using traditional slash-and-burn tech-

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niques of temporary cultivation and continuous rotation through forest fallow. The traditional crop-fallow cycle in the region is 3 years of agricultural cultivation, followed by 9–12 years of forest fallow, after which the plot is cut and burned for subsequent re-use in agriculture (Turner 1983, Turner, Geoghegan, and Foster 2004). This agricultural system is primed for invasion, as the fern becomes established in areas dominated by fires, deforestation, and agricultural activities (Page 1986, Pakeman et al. 1996).

Bracken fern poses exceptional difficulties for farmers in the region. First, fern grows faster than maize, so extra weeding is required so that the fern does not shade the maize; any fern that remains will reduce maize yields. Second, the fern has a persistent underground rhizome, so traditional weeding practices are ineffective at eradicating the invasion. Third, fires are a common practice in the region to clear land for cultivation, and the fern quickly spreads after fires. Finally, the fern impedes forest re-growth, and by itself does not provide enough quality biomass for soil fertility recovery, so an invasion can interrupt the traditional crop-fallow cycle. As a result, once a plot is heavily invaded, some farmers permanently remove the plot from rotation. Previously, land was not abandoned in this system, as after a sufficient fallow period, soil fertility would recover and the land would be returned to agricultural use. Therefore, abandonment due to the fern invasion is a new phenomenon, disrupting traditional crop-fallow cycle dynamics. In addition, as it is such a new phenomenon, there has been no official region-wide policy response to the invasion, so farmers have been attempting to devise management strategies individually.

In this paper, we investigate the factors that affect the decision of a subsistence farmer to either continue cultivating an invaded agricultural plot or permanently abandon the plot and cultivate elsewhere. We develop an agricultural household model of land use choices, where households maximize utility subject to constraints on land, labor, and income. We subsequently test the hypotheses raised, using data from a small household survey performed in the region in 2002. The land abandonment question has potentially important policy considerations, as the study region contains the Calakmul Biosphere Reserve, the second largest nature reserve in Mexico. The spread of bracken fern could potentially lead to further land abandonment and therefore promote greater deforestation in the region, countervailing government policies for conservation surrounding the biosphere reserve. Thus, understanding why farmers abandon invaded plots is not only critical for explaining the social dynamics of the invasion but also for understanding forest conservation and land management in the region.

Land Use in the Southern Yucatán Peninsula Region

This research is part of a larger, multidisciplinary research project that began in 1996 to examine land use changes using satellite, ecological, and household survey data (Turner, Geoghegan, and Foster 2004, Geoghegan et al. 2001). The study region consists of portions of two states in southern Mexico: roughly 20,000 km^2 of land comprising southwestern Quintana Roo and southeastern Campeche, north of the Mexico-Guatemala border. The region is the largest expanse of tropical forest remaining in Mexico (Pérez-Salicrup 2004), and it has been labeled a "hot spot" of tropical deforestation (Achard et al. 1998) due to a rapidly expanding agricultural population. An area of approximately 3,100 km^2 at the center of the region has been designated by the central Mexican government as the Calakmul Biosphere Reserve, with the intent of preventing loss of biotic diversity and providing ecosystem services such as carbon sequestration (see Figure 1).

For the first half of the twentieth century, economic activity here was minimal and centered on the selective logging of tropical woods, particularly mahogany and cedar, as well as on the extraction of chicle, a tree resin used in the production of chewing gum. More extensive deforestation followed with the construction of a two-lane highway across the center of the region in 1967, which opened the frontier to agricultural colonization. Our research focuses specifically on the *ejido* sector of Mexican agriculture, as this is the predominant form of land tenure in the study region. This sector was created following the Mexican Revolution (1910–1917), a political and social upheaval with roots in inequitable land distribution, which resulted in the formation of *ejidos*

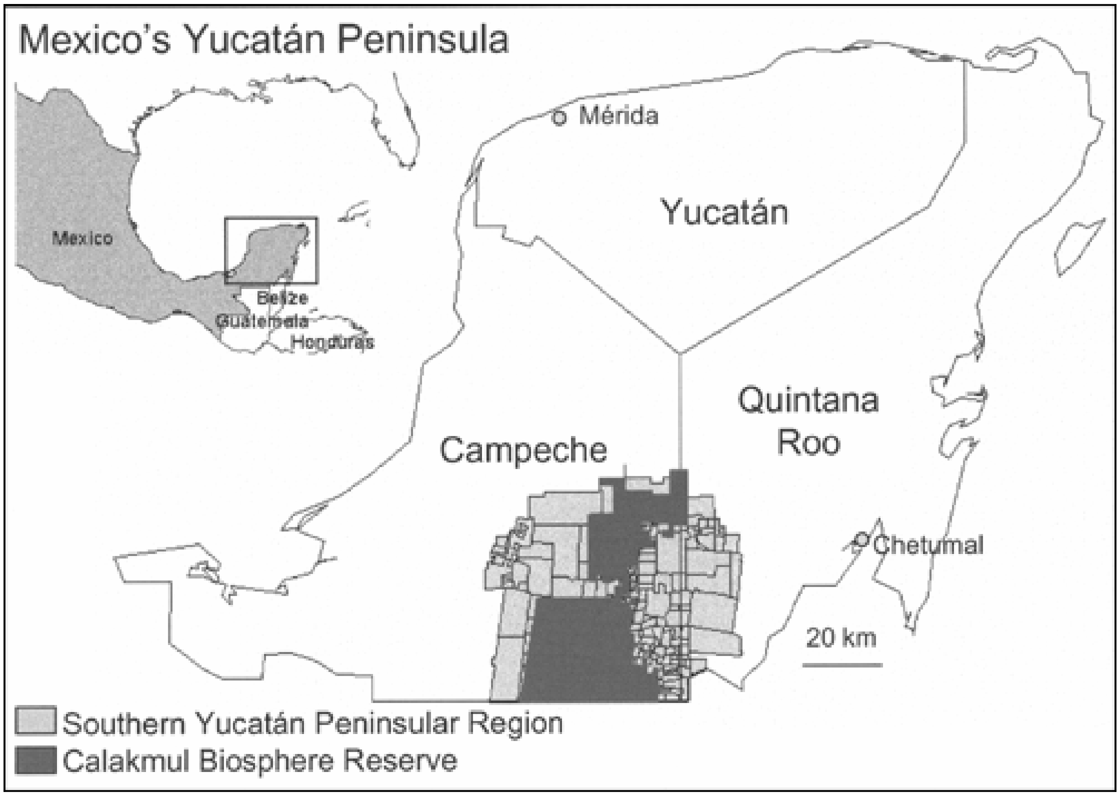

Figure 1. Map of Southern Yucatán Peninsula Region

Source: Adapted from Schneider (2004).

(akin to villages) which consist of land grants from the central government. In our study region, each member of an *ejido* (*ejidatario)* received the same amount of land for use, but *ejidos* settled earlier received much larger tracts of land than those settled more recently. Within *ejido* communities, land is communally regulated by an elected committee, but in this area of southern Mexico, an *ejidatario* typically enjoys usufruct access to a single parcel[1] that is permanently allocated to his use. This tie between households and parcels permits land use decisions to be linked to the geographical locations in which they have impact.[2]

Ecological, Remote Sensing, and Household Survey Data

The data used in this analysis are derived from satellite images, ecological data, and household survey data (Table 1). Satellite images were used to generate land cover data for the region, using Landsat Enhanced Thematic Mapper (ETM+) from 2001. Using remote sensing techniques of principal components analysis and texture analysis, seven classes of land cover were derived from the satellite images: upland forest, wetland forest, late secondary re-growth (7–15 years), agriculture (which includes early secondary re-growth), bracken fern,[3] semi-inundated savannas, and water (Schneider 2004). Using these data, all *ejidos*

[1] "Parcel" refers to the entire land area assigned to individual farmers. "Plots" refers to sections of the parcel under different uses, such as agriculture, fallow, or primary forest.

[2] In 1992 reforms were enacted that terminated the continued extension of *ejidal* land grants. In addition, the reforms gave *ejidatarios* the right to rent or sell their land and to enter into business arrangements with outside investors, all of which were prohibited under the original terms of Article 27. While the long-run consequences of these reforms are potentially profound, research by Klepeis and Vance (2003) suggests that they have had minimal impact on smallholder farmers in the region to date.

[3] Early secondary re-growth, which is vegetation less than approximately seven years old, could not be separated from agriculture in the satellite data, as their spectral signatures are too similar. Areas covered by bracken fern are structurally distinct from forest and agriculture, which allows them to be detected and differentiated in remote sensing analysis.

Table 1. Description of Land Cover, Survey, and Ecological Data

Data	Source	Description
Land cover data	Satellite data: Thematic Mapper and Enhanced Thematic Mapper from 1987 to 2001	7 land cover classes (upland forest, lowland forest, secondary growth, agriculture, bracken fern, inundated savannas, and water)
Survey data	66 household individual farmers' surveys, 46 with fern	(i) Demographic data (per individual farmer): number of children and adults and their age (ii) Land use data: yields, crop-fallow cycles, labor
Ecological data	Digital elevation map	aspect, slope, elevation

in the region were assigned to one of three categories of fern-invasion density: low, medium, and high. From this, an *ejido* from each category was randomly selected to receive the household survey.

The farmers selected for the survey were from the official lists of *ejidatarios*, which were obtained from the chair of the *ejido* (*Comisario Ejidal*). The lists were then divided between *ejidatarios* with and without fern on their lands, and farmers then selected randomly from each category. In those cases in which the selected farmer was not able to participate in the interview, the next random number was selected. A standardized questionnaire was administered to the *ejidatarios* to elicit their socioeconomic characteristics and land use history. To improve the survey instrument, 10 pre-test interviews were performed and the survey instrument adjusted accordingly.

The first section of the survey covered migration history, off-farm employment participation, the demographic composition of the household, farm production and crop-fallow cycle information, and detailed questions on fern for those affected farmers. Completion of the second section involved a guided tour of the agricultural plots associated with each parcel of the respondent. Using a global positioning system (GPS), a geo-referenced sketch map detailing the configuration of land uses was created, which allows a linkage of the individual household survey data to the satellite data. Different *ejidos* have different sized parcels; average plot size for subsistence agricultural use is about two hectares per household in the region, while parcel size ranges from 40 to 100 hectares per *ejidatario*, depending upon which *ejido* he is a member of.

Of the 66 farmers interviewed, 20 were not affected by fern, and of those 46 farmers remaining, 31 farmers had abandoned plots to the fern invasions, moving on to other plots in their parcels, while 15 farmers continued using the invaded plots for agricultural use. While the invaded land must be weeded more frequently than non-invaded land and also results in lower yields, using "new" land requires the higher upfront costs of clearing land that is currently forested. The question we are interested in is, what factors affect the choice of abandonment by these farmers? The theoretical model developed in the next section investigates the optimal land use choices of farmers, given their labor, land, and income constraints.

The Theoretical Model

Theoretical models of shifting cultivation, such as the swidden cycle dynamics observed in southern Mexico, can be found in the agriculture development literature, with a recent focus on the addition of an invasive species into the land use possibility "portfolios" of peasant farmers. The initial contributions in this literature focused on the trade-offs between the higher clearance costs associated with mature forest versus the higher weeding costs associated with inferior soils resulting from continued use of agriculture plots (Dvorak 1992), as well as developing models that viewed swidden cycle dynamics as the optimal control of soil fertility over time (Barrett 1991, Krautkraemer 1994). Subsequent research investigated the difference between clearing primary forest and secondary forest for agricultural use (Pendleton and Howe 2002), and most relevant to this paper, the potential ecological irreversibility of an invasion (Albers and Goldbach 2000, Albers, Goldbach, and Kaffine 2006).

However, the theoretical model used here abstracts away from many of these dynamic aspects, and instead builds on recent research on household agricultural production and forest-clearing in a tropical forest context (e.g., Vance and Geoghegan 2002, Caviglia-Harris 2004, Caviglia-Harris 2005, Vance 2004, Caviglia-Harris and Sills 2005). This literature derives from the agricultural household model developed for the joint consumption and production decisions of agricultural staples by an agricultural household in a developing country context (Singh, Squire, and Strauss 1986, Taylor and Adelman 2003). While the theoretical model presented next is based on the agricultural household model, the crop-fallow cycle dynamic models discussed previously do inform us of the importance of the labor and land constraints in these recurring land use decisions, such as the trade-off between labor spent weeding current agricultural plots versus clearing new land for agriculture, as discussed in Dvorak (1992).

The household grows an agricultural staple (e.g., maize), which the household consumes, with surplus production sold on the market. We assume functioning markets for all inputs and outputs. Production, a twice-differentiable concave function of land and labor, is assumed to be riskless. The planning horizon of the model is one agricultural cycle. Households are assumed to maximize utility, a function of the consumption of the self-produced agricultural staple, (X_a), a purchased commercial good, (X_c), and leisure time, (L_l):

$$\text{Max } U(X_a, X_c, L_l), \tag{1}$$

subject to constraints on labor, land, and income,

$$L = L_n + L_i + L_w + L_l \tag{2}$$

$$A_g + A_i + A_n \leq \hat{A} \tag{3}$$

$$p_c X_c = p_a(Q_i(A_i, L_i) + Q_n(A_n, L_n) - X_a) + w(L_w). \tag{4}$$

The size and demographic composition of the household determines the total labor available per household (L), given in equation (2), which can be used in agricultural production on non-invaded land (L_n) or invaded agricultural land (L_i), off-farm wage-earning labor (L_w), and leisure activities (L_l). Total household land available ($\hat{A}$) (the parcel) is distributed between different uses (the plots)—non-invaded agricultural land (A_n), invaded agricultural land (A_i), and land abandoned for agricultural use because of fern invasion (A_g)—and it is found in equation (3). The income constraint (equation 4) reflects the expenses of the household in purchasing the commercial good (X_c) at its price (P_c), while family income is generated by selling surplus agricultural production ($Q - X_a$) at its price (P_a), as well as off-farm labor (L_w) at the wage rate (w). The absence of a term capturing an explicit rental rate for land in this expression reflects the lack of a land market in the region. Agricultural output, (Q_n) for non-invaded land and (Q_i) for invaded land, is generated through a production function of only land and labor, as maize is grown in the region without chemical inputs. Agricultural productivity of the land decreases with fern invasion, due to the competition from the fern for light and nutrients.

After solving for L_w in equation (2) and substituting into equation (4), the Langrangian for this constrained optimization problem is expressed as

$$\begin{aligned} \text{Max } \mathcal{L} = {} & U(X_a, X_c, L_l) \\ & - \lambda[\, p_c X_c - p_a Q_i(A_i, L_i) - p_a Q_n(A_n, L_n) \\ & + p_a X_a - w(L - L_i - L_n - L_l)] \\ & - \phi(\hat{A} - A_i - A_n - A_g), \end{aligned} \tag{5}$$

where λ and ϕ are the Lagrange multipliers associated with the constraints on income and land, respectively.

The first-order conditions are

$$\partial \mathcal{L} / \partial X_c = \partial U / \partial X_c - \lambda p_c = 0 \tag{6}$$

$$\partial \mathcal{L} / \partial X_a = \partial U / \partial X_a - \lambda p_a = 0 \tag{7}$$

$$\partial \mathcal{L} / \partial L_l = \partial U / \partial \mathrm{L_l} - \lambda w = 0 \tag{8}$$

$$\begin{aligned} \partial \mathcal{L} / \partial \lambda = {} & [p_c X_c - p_a Q_i(A_i, L_i) \\ & - p_a Q_n(A_n, L_n) + p_a X_a \\ & - w(L - L_i - L_n - L_l)] = 0 \end{aligned} \tag{9}$$

$$\begin{aligned} & \partial \mathcal{L} / \partial L_i = \lambda p_a(\partial Q_i / \partial L_i) - \lambda w \leq 0 \\ & \text{and } L_i [\lambda p_a(\partial Q_i / \partial L_i) - \lambda w] = 0 \end{aligned} \tag{10}$$

(11) $\partial \mathcal{L}/\partial L_n = \lambda p_a(\partial Q_n/\partial L_n) - \lambda w = 0$
and $L_n[\lambda p_a(\partial Q_n/\partial L_n) - \lambda w] = 0$

(12) $\partial \mathcal{L}/\partial A_i = \lambda p_a(\partial Q_i/\partial A_i) + \phi \leq 0$
and $A_i[\lambda p_a(\partial Q_i/\partial A_i) + \phi] = 0$

(13) $\partial \mathcal{L}/\partial A_n = \lambda p_a(\partial Q_n/\partial A_n) + \phi \leq 0$
and $A_n[\lambda p_a(\partial Q_n/\partial A_n) + \phi] = 0$

(14) $\partial \mathcal{L}/\partial \phi = \hat{A} - A_i - A_n - A_g \geq 0$
and $\phi(\hat{A} - A_i - A_n - A_g) = 0.$

Equations (6), (7), and (8) represent standard first-order conditions of consumer behavior, assuming that non-zero amounts of each will be consumed. For example, the ratios of marginal utilities from the commercial good and leisure to the shadow value of income are seen to equal the market given price and wage rate, respectively. Equations (10) through (13) reflect the production side of the household. Equations (10) and (11) show that labor will be allocated to each land use (invaded and non-invaded) such that the value of the marginal product is equal to the exogenous wage rate, if there is an interior solution. The Kuhn-Tucker conditions for these equations allow for the optimal allocation of agricultural labor to be zero, which would occur if land were abandoned as a result of the invasion. We assume that an interior solution will always exist for the non-invaded land.

If equation (14) is binding, then $\phi \geq 0$ represents the shadow price for land. Equations (12) and (13) show that the optimal allocation of land between invaded and non-invaded land, assuming an interior solution to both, will be such that the value of the marginal product of land in each use will be equalized. Equations (9) and (14) are the derivatives of the Lagrangian with respect to the Lagrangian multipliers, resulting in a restatement of the constraints.

The first-order condition of most interest to the main question of the paper is equation (12), which indicates that if for invaded land $\lambda p_a \partial Q_i/\partial A_i < \phi$, then there will not be an interior solution, but rather a corner solution: the crop will not be grown on the invaded land and the plot will be abandoned for agricultural use. As the marginal productivity of invaded land falls below some level, the land will be abandoned. However, where equation (14), the land constraint, is less binding, there is a decrease in the shadow price of land, ϕ, so the marginal productivity of land does not have to fall as far in order for abandonment to occur. Therefore, as land availability increases, we hypothesize an increase in the probability of land abandonment.

Similarly, from equation (10), as the marginal productivity of labor on invaded land falls, a larger labor pool will be required to keep the land in production, so it is hypothesized that a larger family size will lead to a decrease in the abandonment of land, all else being equal. Finally, as off-farm opportunities increase, via a higher education level of the head of household leading to a potentially higher off-farm wage rate, the more likely a plot will be abandoned as agricultural production falls.

There are many shortcomings in this theoretical model, some of which we briefly outline here. Agricultural production and the associated labor required for weeding should also be considered a function of years in continuous agricultural use and of fallow length. The longer an agricultural plot is in use, the lower its agricultural output, due to soil fertility decrease over time, while the longer the fallow length, the greater the recovery of soil productivity. In addition, the longer the plot is in use, the greater the amount of labor required to combat the increased number of weeds (Dvorak 1992).

Albers, Goldbach, and Kaffine (2006) derive optimal actions for cropping and fallowing decisions in a two-part, two-state dynamic programming model of optimal rotation, with endogenous fallow lengths. In ongoing research by Ickowitz and Knapp (2005), the authors are developing a simulation model of shifting cultivation where the fallow length is also endogenous. In this modeling framework, the decision to abandon a fern plot could be considered an infinite fallow length. In addition, as clearing new land entails labor during a different part of the season than weeding does, a two-period model, as developed by Pendleton and Howe (2002) could explicitly consider these trade-offs. We abstract away from these dynamics as we currently have available only cross-sectional data on land use, derived from the survey instrument. In the future, time-series data on land use will be determined from the satellite data, in order to explicitly address these dynamic land use issues. However, in the current context, by not explicitly considering these dynamic aspects in the empirical model that follows, it is possible that we erroneously rejected some hypotheses.

The Empirical Specification and Results

As suggested by the theoretical model presented above, the land abandonment decision is based on a comparison of the returns of continuing to use an invaded plot to the returns of other options available to the land manager. There are several testable hypotheses that result from the theoretical model, specifically concerning the effects of labor supply and the land constraint on the abandonment decision. The effect of the labor pool, L, measured by household size, is predicted to negatively affect abandonment, as we predict that the increase in the size of the labor pool available for weeding should keep invaded land in production longer.

To estimate the effect of the land constraint $\hat{A}$ that a farmer faces, we include the total forest remaining on a parcel, consisting of the sum of land currently in secondary growth and primary forest. We expect that the larger the remaining forest available to a household, the greater the probability of abandonment, as the shadow price of remaining land decreases with the increased supply of potential agricultural land.

We have no direct information on the off-farm wage, w, for each farmer, so we include a proxy for whether the head of household has had any formal education. We expect that educated farmers have potentially higher off-farm income-generating labor possibilities. The theoretical model also includes prices of other goods, but as these do not vary across the study region, they are not included in the empirical specification.

From the theoretical model, we expect the land and labor constraints to be the main factors affecting the abandonment choice, but also control for other characteristics. The ecological literature suggests that land use practices affect the establishment of the fern, so we control for this by including the number of years, on average, a "typical" plot in each farmer's parcel is used to cultivate *milpa*.[4] As bracken fern thrives in sunny and dry conditions, slopes that face northeast have these preferred light and humidity conditions during the critical summer growing season.[5] We control for this by including the aspect of the plot, which measures the direction the maximum slope faces.[6]

While the survey instrument included questions concerning numerous features of the households, given the small size of our sample of interviewed farmers that have fern on their parcels (N = 46) we use a very parsimonious specification of the empirical model. The data are structured so that there is a single cross-section of observations associated with each farmer who had fern on his parcel in the 2002 survey. Descriptive statistics of these variables can be found in Table 2.

The decision to abandon land after a fern invasion decision is modeled as a fixed-effects logit model, with the effect at the *ejido* level, as we suspect that the errors within an *ejido* are correlated, due to unobserved differences in each *ejido*, such as institutional variation like access to government and nongovernmental programs in the region. Specifically, the fixed-effects logit model estimates the probability of abandonment as

$$(15) \qquad \Pr(Y_{it} = 1 \mid X_{it}) = \frac{\exp(\alpha_i + X_{it}\beta)}{1 + \exp(\alpha_i + X_{it}\beta)},$$

where $i = 1, \ldots, n$ denotes the independent groups—in this case the three *ejidos*—and $t = 1, \ldots, T_i$ denotes the observations in each *ejido*. The results from this model can be found in Table 3.

The estimated coefficient on household size is negative, but not statistically significant, so we

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[4] This is not the number of years the fern-invaded plot has been in agricultural production, but rather the response to the survey question of "how many continuous years have you historically used a plot for *milpa* before letting it go in to fallow?"

[5] Bracken fern plots seem to prefer slopes facing northeast; this could be explained by the plant micro-climate preferences. In middle latitudes, such as the southern Yucatán, the contrast of aspects could be sufficiently strong to produce some differentiation of the vegetation in very close distances. An explanation of why bracken fern seems to dominate slopes facing northeast is, first, that the east-facing slopes are usually hit by the sun directly in the morning; in these areas, then, the humidity carried through the night dries faster and temperatures in the soil increase. Second, the period from May to June, when the sun rises from the northeast, is the period when most of the fires occur, and new bracken fern colonies are established.

[6] Aspect is measured in decimal degrees, using standard azimuth designations, with due north as zero degrees and going clockwise to 360 degrees (e.g., northeast = 90).

Table 2. Descriptive Statistics

Variable	Description	Mean	Std. Dev.	Min.	Max.
DEPENDENT VARIABLES					
Abandonment	If invaded plot is abandoned	0.67	0.47	0	1
EXPLANATORY VARIABLES					
Household Size	Number of household members	4.46	1.86	1	9
Education	Dummy variable for education of head of the household: 0 = no education, 1 = some education	0.67	0.47	0	1
Years Agricultural Use	Average number of years over an entire parcel a farmer keeps a "typical" plot in subsistence agricultural production	3.17	2.54	1	10
Ejido	Dummy variable for ejido type: 1 = Ejido 1, 2 = Ejido 2, 3 = Ejido 3	2.28	0.86	1	3
Aspect	Direction in which the maximum slope faces (measured in degrees)	148	44	83	234
Total Forest	Hectares of forested land: primary and secondary growth	50.87	27.93	0	100

Table 3. Fixed-Effects Logit and Pooled Probit Estimation Results of Abandonment or Not (sample size = 46)

	Fixed-Effects Logit		Pooled Probit	
	Marginal Effect	Z	Marginal Effect	Z
Household size	−0.31	−1.39	−0.16	−1.30
Education	1.74**	1.96	1.02***	2.02
Years agricultural use	−0.44***	−2.41	−0.26***	−2.60
Aspect	−0.012	−1.04	−0.005	−0.88
Total forest	−0.009	−0.50	−0.015*	−1.55
	Log likelihood = -17.24	LR chi2 (5) = 13.82 Prob > chi2 = 0.017	Log likelihood.= -22.20	LR chi2(5) = 13.68 Prob > chi2 = 0.018

Notes: * is statistically significant at 85 percent, ** is statistically significant at 90 percent, *** is statistically significant at 95 percent.

are not able to conclude that larger households are less likely to abandon their invaded plots. The estimated coefficient for education is positive and statistically significant at the 90 percent level. All else being equal, having some level of formal education results in an increased probability of abandonment, confirming the *a priori* expectation that farmers with some education have greater opportunity costs to their time.

The estimated coefficient on the average number of years that a farmer keeps a "typical" plot in his parcel in subsistence agricultural production (*Years Agricultural Use*) is negative and statistically significant. The longer a given plot is kept in continuous agricultural production, all else being equal, the smaller the probability of abandonment after the fern invasion. This result has potentially interesting policy implications. From the ecological literature cited above, the longer a plot of land is continuously used in agriculture, the greater the increase in the probability of invasion. However, this finding suggests that the longer, on average, a farmer decides to continuously use an agricultural plot, the less likely he is to abandon a plot due to a fern invasion. Therefore, any potential policy designed to reduce fern invasion based solely on the ecological literature—such as one that gives incentives to farmers to shorten their crop-fallow cycles that does not take into account a farmer's response to the invasion—could potentially result in the unintended outcome of increase in land abandonment.

The physiographic variable aspect (*Aspect*) was not found to be statistically significant in this specification, likely a result of the way this variable is currently calculated. All of the variables in the model are parcel-specific, not plot-specific; therefore, this variable is calculated by averaging the value over the entire parcel. It is quite possible, then, that the average aspect for an entire parcel does not affect the abandonment decision, but that the aspect of a particular plot could affect the decision to abandon that specific plot. Future research will focus on developing models that are spatially explicit, so that variables such as aspect can vary across plots within each parcel.

Given our theoretical framework, the most surprising outcome from the empirical specification is the statistically insignificant result on the total amount of forest (*Total Forest*). We had expected this variable to be positively related to abandonment, as, with a greater amount of "new" land available, the lower the shadow value of new land. However, there is very little variation in this variable at the *ejido* level, potentially leading to this statistically insignificant result in the fixed-effects model, as this model uses variation only within each *ejido* to identify the effect of forest size on abandonment. As a result, we re-specified the model as a probit model and pooled all the observations in order to allow this effect to be observed using between-*ejido* variation. The results of this model are found in Table 3, together with the results of the fixed-effects logit model.

The estimation results between the two specifications are qualitatively similar, except for the total forest variable, which is now statistically significant at the 85 percent level, somewhat confirming the hypothesis that larger land holdings decrease the probability of abandonment. However, these results could also be an expression of the inadequacy of using a static cross-sectional model to attempt to capture these dynamic land use decisions. Given the large land holdings in the region, the effect of the land use constraint might manifest itself only over a longer time frame.

Conclusions and Further Research

The main hypotheses derived from the theoretical model of land use concern the constraints on land and labor and the opportunity cost of time. We had hypothesized that individuals with smaller land holdings, specifically with smaller amounts of remaining forest, would be less likely to abandon invaded areas. This hypothesis was somewhat supported by the empirical results. The hypothesis concerning the labor constraint was not supported. However, the hypothesis concerning the influence on the wage rate, proxied via the education variable, was established, demonstrating that farmers with greater off-farm labor options were more likely to abandon an invaded plot.

Empirical research on individual behavioral responses to invasive species is scant, as most of the literature to date has focused on theoretical aspects. However, other empirical research on land-clearing of forests for agricultural use in a semi-subsistence framework also finds that household size and education are important determinants of this decision [for example, Pendleton and Howe (2000) for Bolivia, Caviglia-Harris (2004) for Brazil, and Vance and Geoghegan (2002) and Geoghegan, Schneider, and Vance (2004) for this same region of Mexico]. Other research has found that lot size is a statistically significant factor in land-clearing in Ecuador (Pinchón 1997) and Brazil (Caviglia-Harris 2004), but given the different institutional structure of land tenure in Mexico due to the history of the *ejido* system, our result is not directly comparable.

The interactions among land use practices, deforestation, and fern invasion are complex and are only preliminarily addressed here. However, as discussed above, a potentially important policy-relevant result from this study is that farmers who keep their agricultural plots in continuous production longer are less likely to abandon these plots after invasion. As many governmental and non-governmental organizations are involved with trying to reduce deforestation in the region in order to help protect the biodiversity and other ecological goods associated with the Calakmul Biosphere Reserve, any policy designed to affect land use decisions in the region must take into consideration the impact on the spread of bracken fern and the response of farmers to the invasion.

We have available a rich dataset on individual agricultural choices in a subsistence context, which links household survey data with satellite data and other ecological data. Our initial investigation into agricultural land abandonment due to an invasive species suggests a potentially complex relationship between those choices and crop-fallow cycle choices. Therefore, the next phase of this research will consider the fallow length and cropping duration choices explicitly, by developing a dynamic theoretical crop-fallow cycle model, as suggested by some of the contributions in the literature reviewed above.

Related project research analyzing the impacts of crop-fallow cycle dynamics on soil quality is ongoing. The results from that ecological work could then be incorporated as a biophysical feedback into the next modeling endeavor. Such biophysical feedbacks have long been called for but are virtually absent in economic modeling. Finally, in addition to relying on each farmer's responses to questions concerning these choices, we also have available time-series satellite data that have yet to be analyzed. As a result, we can derive past land use decisions independent of an individual's ability to recall previous decisions to generate the time-series data necessary for the analysis.

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