The Diffusion of Cattle Ranching and Deforestation: Prospects for a Hollow Frontier in Mexico's Yucatán

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ABSTRACT. *This article investigates the behavioral drivers of pasture creation and associated implications for deforestation in a 22,000 km² agricultural frontier spanning the base of Mexico's southern Yucatán. After developing a theoretical model that highlights the role of social networks and information spillovers with respect to the decision to begin cattle ranching, we use household data to estimate an econometric duration model of the determinants of pasture creation. Although pasture fits well with the typical household's resource constraints, its continued expansion contributes to a hollow frontier dynamic in which the spread of low-value cattle ranching coincides with decreasing population.* (JEL Q15, R22)

I. INTRODUCTION

Few human endeavors are as emblematic of the tensions between economic development and environmental stewardship as livestock production. Employing some one billion of the world's poor, the livestock sector generates 18% of greenhouse gas emissions and consumes 30% of the planet's terrestrial surface, making it the single largest anthropogenic user of land (FAO 2006, xxi). The consequences of this land intake are particularly profound in the world's tropical biomes, such as those of Latin America, where pasture is the principal land use displacing the forests. This conversion not only affects global climate, but also poses more immediate regional and local concerns, including soil erosion, water scarcity, and plague outbreaks.

Attempts to understand the causes of pasture creation have largely focused on the Brazilian Amazon, where poorly defined property rights and land speculation are frequently cited as factors that encourage clearance by ranchers with little interest in the productive value of the land, per se (Holston 1991; Hecht 1985). In many other parts of Latin America, however, cattle ranching is increasingly undertaken by smallholder farmers, who incorporate pasture as part of a land use portfolio that includes mixed subsistence and commercial crop cultivation. Although such agents have been identified throughout the region, including in the Caribbean (Brothers 1997), Costa Rica (Sader and Joyce 1988), Mexico (Durand and Lazos 2004; Schmook and Vance 2009), and other Central American countries (Jones 1989), the motivations underpinning their decision to plant pasture remain poorly understood.

The present paper aims to fill this void with an investigation of the behavioral drivers of pasture creation in a 22,000 km² agricultural frontier spanning the base of Mexico's southern Yucatán (SY). As Durand and Lazos (2004) document, Mexico has been the site of particularly extensive cattle ranching by smallholder farmers, largely resulting from the country's success in attracting credits from the World Bank and Inter-American Development Bank for cattle ranching projects. Between 1960 and 1980, pasture in southern Mexico increased by 156% (Rutsch 1980; Toledo 1991), with about 60% of net carbon emissions in the country attributable to the conversion of closed forests to pasture in 1985 (Masera, Ordóñez, and Dirzo 1997).

The study site considered here is the most remote and least populated part of the Yucatán Peninsula, which, together with contiguous forestland across the border in Guatemala and Belize, contains the largest area of tropical forest outside of the Amazon in the Western

Land Economics • November 2011 • 87 (4): 682–698
ISSN 0023-7639; E-ISSN 1543-8325

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Hemisphere. During the 1970s and early 1980s, the SY received massive inflows of state-financed investment, beginning with the construction of a highway through its center in 1972 that instigated the first influx of agricultural colonists. Since that time, deforestation has continued unabated, with annual rates ranging between 0.32% and 0.39% between 1969 and 1997 (Turner et al. 2001). We examine the causes of this conversion through a combination of descriptive analysis and econometric modeling of farm-household data. The econometric specification is motivated by a theoretical model that focuses specifically on the role of information-spillovers among neighboring farmers in spurring the diffusion of pasture. Our analysis suggests that cattle ranching has been an important determinant of deforestation, that it has spread increasingly to new adopters, and that it appears poised to be the key driver of land use change in coming years.

The article concludes by considering future prospects for development and deforestation in the SY through the lens of the hollow frontier concept articulated by Rudel, Bates, and Machinguiashi (2002). We explore the possibility that the diffusion of low-value pasture in the SY might continue in tandem with the recent trend toward greater migration to the United States, an outcome that would be consistent with a hollow frontier development trajectory.[1] Reversing this trajectory would involve cuts in the distortionary incentives that artificially bolster deforestation, ideally coupled with dissemination campaigns strategically targeted to harness the flow of information about forest benefits among the region's farmers. Given the low profitability of cattle in the region, our findings suggest considerable scope for cost-effective measures to encourage reforestation through the retirement of lands currently planted under pasture.

II. THE LOGIC OF PASTURE EXPANSION

Despite much past research in the SY, the factors governing the largest category of agricultural land use in the region—pasture for cattle—have remained mostly unexplained: "The rationale for investing in pasture, other than payments that assisted this effort, is not well understood" (Turner, Geoghegan, and Foster 2004, 294). We conclude from direct evidence from the survey work and econometric results that cattle ranching is spreading as an agricultural activity because (1) it is so well suited to the typical household resource constraints in the region; in particular, farmers have abundant land (a mean of approximately 68 hectares) but relatively scarce labor; (2) it is a less risky activity than crop cultivation and can in fact serve to reduce household vulnerability; (3) it has received substantial support from government programs including loans, subsidies, and material support; (4) modest income gains, derived at least in part from cultivation of jalapeno chili peppers—the region's main cash crop—have enabled more and more households to cover the startup costs associated with cattle ranching; and (5) social spillover effects and greater opportunities for learning by observing have reduced learning costs, thereby spurring diffusion.

In the five years leading up to our fieldwork, the expansion of pasture for cattle drove net forest loss. From 1997 to 2003, the amount of land covered by pasture increased at a rate of 0.67% yr^{-1} and the area devoted to crops fell by 0.39% yr^{-1}, for a net annual deforestation rate of 0.28%.[2] Also over that time period, there was a sharp increase in the number of households practicing cattle ranching. The accelerating spread of cattle ranching among household farmers can be illustrated with a

[1] A "hollow frontier" development trajectory can be contrasted with the "forest transition" pathway in which increasing industrialization and gains in agricultural productivity enable significant reforestation to follow extensive land use and deforestation (Defries, Asner, and Houghton 2004; Rudel et al. 2005), as has been evident in much of North America and Europe (Walker 1993; Mather and Needle 1998).

[2] This is the rate of forest loss on land under the management of smallholding farmers with primary and secondary forest treated equally (i.e., if forest regrowth is occurring on a parcel previously devoted to agricultural use, it is not considered deforested). Excluded from the calculation are communal lands (some of which are managed for timber extraction) and protected areas such as the Calakmul Biosphere Reserve.

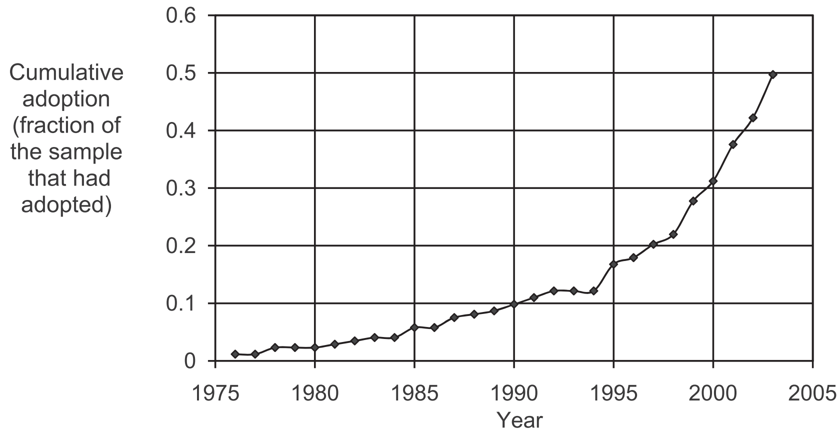

FIGURE 1
Diffusion of Cattle Ranching: Adoption over Time by Households in the Southern Yucatán

diffusion curve. In Figure 1 we plot the cumulative adoption rate over time.

The figure illustrates the clear trend toward an increasing marginal rate of adoption. Four of the five highest marginal rates of adoption occurred over the five years prior to our survey. The result is a diffusion curve that looks to be at a point within the "takeoff period" described in the literature on diffusion of new technologies (Sunding and Zilberman 2001; Feder, Just, and Zilberman 1985).

Pasture as a land use and cattle ranching as an activity are spreading, and the result is a radical change in the smallholding farmer's capacity to transform the land. Pasture for cattle effectively relaxes the constraints on labor (more precisely, it requires less labor and so the constraint binds only when more land is used) and eliminates the soil fertility constraints that limit the extent to which the other major agricultural land uses, in particular the crops maize and jalapeno chili peppers, lead to deforestation. Pasture can be grown permanently, or nearly so, if properly maintained. In contrast, crop production in the SY typically involves shifting (i.e., slash-and-burn) cultivation in which farmers cultivate crops for a few years and then abandon the land, which allows reforestation to occur. Forest regrowth builds up biomass that can later be burned to enrich the soil just before the next cultivation cycle.

For a smallholding household with aspirations to begin cattle ranching, a frequent approach is to accumulate pasture over time by planting pasture grasses after a year or two of cultivating crops. Thus, pasture substitutes for land that would have otherwise been returned to secondary forest status if the smallholder had not adopted cattle ranching. Forest succession is thereby suppressed. We can see in Table 1 that pasture increases the capacity for smallholding farmers to transform their forestland to agricultural use when we split our sample and show land uses by those practicing cattle ranching and not, and then only for households with mature cattle ranching operations defined as those who have had pasture for cattle for at least 10 years.

The mean of total agricultural land use for those with pasture is 26.1 ha, seven times larger than for those without any pasture. Moreover, since many of those with pasture are only just beginning to establish their cattle ranching operation, the difference is even greater for those with mature cattle ranching operations, who have land use more than an order of magnitude larger than those without pasture (nearly 12 times larger). Farmers without pasture invariably maintain a larger proportion—roughly 94%—of their parcel in forest. By contrast, those who adopt pasture greatly increase their capacity to transform their parcel from forest cover to agricultural

TABLE 1
Land Area in Hectares for Different Types of Households, Mean 2003 Data

		Land Covers		Principal Land Uses		
Household Type (Cases)	Total	Forested	Cultivated	Pasture	Maize	Chili
All (165)	68	53.1	14.9	11	3.7	0.52
Nonadopters (75)	65	61.3	3.7	0	3.1	0.56
Adopters (90)	75	48.9	26.1	21	4.2	0.49
Mature adopters (26)	93	50	43	38	4.5	0.47

Note: The All category includes nonadopters and adopters, with adopters defined as those households with pasture for cattle. Mature adopters are those that have had pasture for cattle for at least 10 years. Only households with at least ¼ ha in use for agriculture are included. Eight cases without appreciable agriculture land use include instances in which the head of household had lucrative off-farm employment, had migrated to the United States or another part of Mexico in search of employment, or was disabled.

use, maintaining roughly 65% of their parcel in forest.

Despite its large land requirements, cattle ranching is relatively less labor intensive than either chili or maize. In particular, the harvest of chili requires intensive bursts of labor that almost always exceed the family supply of labor, and each field is usually harvested three to four times in a season. Developing the infrastructure necessary for cattle ranching, especially fence construction, is labor intensive. But this can be done piecemeal, unlike chili harvesting, which involves strict timing to maximize production and avoid spoilage. While cattle ranching offers the lowest returns on both the dollars per hectare and dollars per kilogram dimensions, it provides the best return from the perspective of return for each day of labor invested (Busch and Geoghegan 2010).

Not only does cattle ranching use relatively less labor and relax soil constraints, it has favorable attributes vis-à-vis risk and vulnerability. We asked open-ended questions to elicit attitudes about risk and to probe the decision to adopt.[3] Cattle are more robust than crops in the face of the climatic extremes that periodically visit the area (such as drought or hurricane). Cattle are much more likely to survive hurricanes. Almost all of the region's agriculture lacks irrigation (none in our sample), leaving crops at risk when precipitation fails to materialize. Cattle also require substantial amounts of water, especially in extreme heat. But during the hottest, driest periods, ranchers can deliver water to their cattle; this is infeasible for large areas of cropland, given the lack of established irrigation systems. Cattle is not only less risky on the production side, but serves as a wealth accumulation strategy and a type of bank account for people far from financial institutions, and so dampens vulnerability on the consumption side of life for the household farmers of the SY.

III. THEORETICAL FRAMEWORK: A MODEL WITH LEARNING FROM OTHERS

Given the importance of the SY's forestland and the potential for cattle ranching to lead to much greater deforestation rates, the determinants of its adoption are of interest. Beginning a new agricultural activity such as cattle ranching is a type of technological change. Modern scholarly work has identified two distinct, though interrelated, aspects of technological change: the generation of innovations and their diffusion throughout society. In this article, we focus on the diffusion of cattle ranching. Though some tailoring of the technology to local conditions (i.e., innovation) has occurred and is ongoing in the SY, the phenomenon of adoption is the larger issue for understanding the land use impacts that will follow from evolution of the cattle sector.

The modern study of diffusion from an economic perspective originated with Griliches (1957, 1958), who began to establish systemic regularities common to diffusion processes, notably the frequent observation of an S-

[3] See Busch (2006) for a full discussion of responses to these and other questions.

shaped curve over the technology's lifetime (with time on the x axis and percentage of adopters on the y axis). Diffusion often includes the following stages: Marginal rate increase over early adoption and then there is a takeoff period during which the marginal rate peaks. At some inflection point begins a phase of decreasing marginal returns that continues until saturation is reached. Finally, most technologies eventually go into decline as they are replaced with new ones. This search for such systemic regularities in diffusion over time has been termed the imitation modeling approach. The approach has been used fruitfully to parameterize time-series data on aggregate adoption. Nevertheless, dissatisfaction with its lack of explicit treatment of the agent's decision-making process led to renewed emphasis on an alternative technique referred to as threshold modeling (Sunding and Zilberman 2001), which explores the role of heterogeneity among producers in the timing of adoption.

Here we adopt the threshold modeling technique to explore the role of social networks and learning in the diffusion of pasture. Specifically, we develop a model of technology adoption with social learning that modifies a framework known as the target input model (Bardhan 1999; Foster and Rosenzweig 1995). Some aspect of a new technology is understood with certainty, but the farmer's understanding of the technology is limited by the presence of a random parameter that reflects the bounds of understanding. As an example, Bardhan (1999) suggests thinking of the new technology as a seed that depends upon local characteristics such as soil quality and that requires some amount of fertilizer as an input. A key input that fits this conceptual framework in the cattle ranching sector in the SY is the artificial pond that all cattle ranchers must dig in order to provide water for their cattle during the dry season. This is a major expense for adopters and is sensitive to local conditions (in particular, the amount of precipitation). It is thus subject to learning.

First define a production function[4]

$$q_{it} = 1 - (k_{it} - \kappa_{it})^2, \qquad [1]$$

where k_{it} is defined as the level of input use for person i at time t, and κ_{it} is the target level of input use. κ_{it}, unknown at the time that input levels are chosen by the farmer, is defined as

$$\kappa_{it} = \kappa^* + \mu_{it}, \qquad [2]$$

where μ_{it} is a normally distributed independent and identically distributed shock with mean zero and variance σ^2_{it}. The farmer does not precisely know κ^* but has some beliefs about the true value. These beliefs are characterized by the distribution $N(\kappa^*, \sigma^2_{\kappa it})$. Thus, learning in the model is a process of gathering information in order to gain increasing certainty about the optimal value κ^*.

A simplifying assumption that does not affect the analysis of the learning process, but that does simplify the analysis of the adoption decision, is that inputs are costless. This would mean that output equals profit. Maximization of profit in this framework requires that $k_{it} = E(\kappa_{it}) = \kappa^*$ and implies that expected profit can be defined as

$$E_t(q_{it}) = 1 - \sigma^2_{\kappa it} - \sigma^2_u. \qquad [3]$$

Thus, as the farmer learns about the technology, that is, about the true value of κ^*, the magnitude of $\sigma^2_{\kappa it}$ decreases, and expected profit grows.

Now apply the target input model to explore learning-by-observing. The assumption is that farmer i is able to observe the input choices and output results of each farmer j that lives in the same village and has no other sources for learning. In reality social networks are more complicated. They extend beyond village boundaries and there may be divisions within the village itself. Nonetheless the village is a reasonable approximation for the social network in the SY, where their remoteness renders many settlements isolated. We consequently use the fraction of village that has adopted to explore social spillover effects in our econometric work.

In the model, the farmer observes only imperfectly the input levels of her neighbors, so we add a stochastic element to the expression. Farmer i observes $\kappa_{jt} + \varepsilon_{jt}$, with

[4] The exposition here closely follows Bardhan (1999).

$\varepsilon_{jt} \sim N(0,\sigma_{\varepsilon}^2)$.[5] Let $1/\sigma_{\kappa it}^2 \equiv \rho_{i0}$, the precision of the initial beliefs of farmer i about the value of κ^*. Further, define

$$\rho_v = \frac{1}{\sigma_u^2 + \sigma_\varepsilon^2} < \rho_0 \qquad [4]$$

and

$$\sigma_{\kappa it}^2 = \frac{1}{\rho_{i0} + N_{t-1}\rho_v}, \qquad [5]$$

with N_{t-1} defined as the numbers of times that the farmer has been able to observe the technology in use by her neighbors up to time $t-1$. We can rewrite expected profits as dependent upon the number of trials previously conducted by others in the village:

$$Eq_{it}(N_{t-1}) = 1 - \frac{1}{\rho_{i0} - N_{t-1}\rho_v} - \sigma_u^2. \qquad [6]$$

Now, by referencing the first- and second-order conditions, we can formally characterize the information spillover resulting from the greater experience of neighbors with the new technology:

$$\frac{\partial Eq_t(N_{t-1})}{\partial N_{t-1}} = \frac{\rho_v}{(\rho_{i0} + N_{t-1}\rho_v)^2} > 0 \qquad [7]$$

and

$$\frac{\partial^2 Eq_t(N_{t-1})}{\partial N_{t-1}^2} = \frac{-2\rho_v^2}{(\rho_{io} + N_{t-1}\rho_v)^3} < 0. \qquad [8]$$

The expected profits of farmer i increase at a decreasing rate in the number of trials previously conducted by her neighbors. Thus, we arrive at the intuitively appealing result that the greater the stock of adopters in a village, the lesser the learning cost to any particular farmer due to information spillovers, an effect that tapers off as the stock increases. Such a nonlinearity is identified empirically by Bandiera and Rasul (2006), who find an inverted-U relationship between the probability of adopting a new crop and the adoption choices of the farmer's family and friends among farm households in Mozambique.

[5] The model relies on the not particularly realistic assumption that σ_u^2 and σ_ε^2 are known to the farmer. The assumption is not strictly necessary but increases the simplicity of the analysis.

IV. EMPIRICAL METHODS

The Econometric Model

To test this hypothesis in the context of the SY, we develop a duration model that looks at the timing of household adoption of cattle ranching. Specifically, we employ Cox's proportional hazard model (Cox 1972; Cox and Oakes 1984), a highly flexible semiparametric model that is considerably more robust than standard regressionlike approaches to hazard modeling (Allison 1995; Vance and Geoghegan 2002). The proportional hazard model is formulated as (suppressing time subscripts)

$$\lambda(t_i) = e^{-\beta' x_i}\lambda_0(t_i),$$

where the function $\lambda_0(t_i)$ is called the baseline hazard. The term "hazard" is used to refer to the chance that the discrete event being studied, often called a failure, will occur. In our model, the failure under consideration—the dependent variable—is whether to adopt cattle ranching. Unlike parametric duration models, the Cox method requires no particular probability distribution to represent survival times. The baseline hazard depends only on the length of the spell, t. All individuals (indicated by the subscript i) share the same baseline hazard function, which can take on any form other than being negative. The overall hazard rate for any particular individual, $\lambda(t_i)$, is shifted by the other right-hand-side term, $e^{\beta' x_i}$, and in this way the model accounts for heterogeneity across observational units (across households in our model).

Another attractive feature of the proportional hazard model is the ease with which its partial likelihood framework readily accommodates censored data. We observe adoption occurring at an increasing rate. Moreover, there are indications that governmental inducements to support the activity will continue, and most of those that have not yet adopted profess a desire to adopt. So it is appropriate to view the data as censored. The "experiment" is incomplete for those households that have not yet adopted. The proportional hazard model accounts for censoring as follows: for a household censored between time t and $t + 1$, the household is included in the denominator of the contribution to the log-likelihood for observations at time $1, \ldots, t$, but not in $t + 1$ or any thereafter.

Estimation is carried out with a robust estimator of the variance-covariance matrix for coefficients, which enables use of robust standard errors for purposes of inference (Lin and Wei 1989). The robust approach accounts for potential correlation across observations for a given respondent. Finally, as is typical for duration data, the data analyzed here contains a large number of ties, that is, observations for which a failure occurs at the same time. To accommodate this feature, the model is estimated using the approximation method proposed by Efron (1977).

Survey Methods

The data used in this paper draw on a household survey conducted in 2004 of 173 households in 13 *ejidos* (villages).[6] Our data collection effort built on a random sample collected in 1998 by the Southern Yucatán Peninsular Region Project, a large-scale, interdisciplinary research project focused on the study area (Turner, Geoghegan, and Foster 2004). The original sampling of households was accomplished via a stratified two-stage, cluster design (Deaton 1997) with the first stage involving random selection of ejidos and the second stage involving random selection of landholding households within each selected ejido. Ejidos were separated into strata according to agroecological zone and distance from markets and roads. Then ejidos within each stratum were weighted according to their size relative to the stratum population, and one ejido was chosen from within each. Next, households were chosen at random from within the sampled ejidos.

We located 138 households of the group that had been previously surveyed in 1998.[7] We added households with heads under 22 from the 11 ejidos in the original sample to correct for the loss of household heads remaining at the lower end of the age range. We also sought better representation of the south-central area of the region, whose population had increased at a relatively faster rate than other parts of the region. Again using a stratified two-stage, cluster design, we added 23 households from two villages in this south-central part of the study area.[8]

From each household we collected a wide range of demographic and socioeconomic data on the household and biophysical data on their land.[9] We collected data on all categories of land use and forest cover and all inputs, outputs, and revenues from production of crops, livestock (cattle and sheep), beekeeping, and agroforestry. We asked open-ended questions about agricultural strategies, losses from drought and hurricane, strategies for dealing with these, technological choices (reasons for adopting, never adopting, or adopting and then quitting), sources of information for new technologies, and social networks.

We constructed time-varying covariates from our primarily cross-sectional data to address the dynamic question of what determines the timing of pasture adoption. In addition to the year the household started cattle ranching, we have a number of key variables that offer some temporal variation,

[6] Ejidos are social institutions defined under Mexico's constitution. For the purposes of this article, the reader can simply think of these as villages. For many years, ejidos consisted strictly of common property—individuals could manage their own parcels, but rights were strictly usufruct. Recently changes to Mexican law allow ejidos to divide and title land for individual ownership. None of the ejidos in our sample have done this, and it is very uncommon in the SY. Though land in the SY remains mostly held as common property, it is also true that agriculture almost always occurs on individually managed parcels and not in open-access arrangements. For more see Klepeis and Chowdhury (2001).

[7] Most of those that we could not find had moved away. Of note were five refusals and also four cases of physical or mental incapacitation.

[8] We added these 23 households also following the stratified two-stage cluster approach. We picked one ejido each from a northern stratum and a southern stratum, and then randomly sampled from within these ejidos.

[9] For a more complete description of sample selection and data collection, including a complete list of the more than 1,000 variables included in the three survey instruments, see Busch (2006).

including the number of years that the household grew chili in advance of adopting cattle ranching, income support payments for farmers (a program known as the PROCAMPO program, which began in 1995), and the age of the household head in each year.

Using this information, we developed a panel dataset that goes back to 1950, the year the first household in our sample was formed. In most cases the year of formation is defined as the year the household head moved to the region. In a few cases in which the household head moved to the region as a child with his family, the year of household formation is defined as the year the household head moved out of his parents' house. The unit of observation in the data is given by a household-year combination. On average, the 173 households in the data are observed over 16.28 years, yielding a dataset comprised of 2,816 observations.

Explanatory Variables

The model specification includes a suite of static and time-varying covariates that are hypothesized to influence the timing of adoption, the expected signs for which are discussed in the following.

Village network. Following directly from the preceding theoretical model, we hypothesize that a greater stock of adopters, as measured by the one-year lagged percentage of adopters in the village and its square, will increase the probability of adoption at a decreasing rate. The use of the village as the exogenous domain of the information network follows several studies that address social learning in agriculture (e.g., Besley and Case 1994; Foster and Rosenzweig 1995; Munshi 2004). Other studies in this vein have used lists of contacts reported by the respondent (e.g., Conley and Udry 2010; Bandiera and Rasul 2006) or neighboring GIS readings (Robalino and Pfaff 2009) to construct the social network. Given that individuals tend to interact with those who are similar to them, one advantage of using the village as the social network is that it is less prone to endogeneity problems that might afflict information drawn from a self-reported reference group (Munshi 2008, 3106).

Prior years of chili cultivation. Cattle ranching involves relatively large startup costs compared to crops such as jalapeño chili or maize, and so we sought a measure of liquidity over time. For this we develop an admittedly imperfect proxy: number of years that the farmer has previously cultivated chili. Jalapeño chili peppers are the key cash crop and a primary source of income for residents of the SY. Thus, we hypothesize that a greater number of years previously cultivating jalapeño chili will positively affect the chance of adoption.

Government inducements. In 1994, the Mexican federal government changed its system of rural income support, moving away from specific crop subsidies, in order to be in compliance with the North American Free Trade Agreement. The centerpiece of the new agricultural policy was the PROCAMPO program, which bases income support payments on the area devoted to agricultural land use in 1994. We capture its effect with a measure of the number of hectares that the household has in PROCAMPO for each year. This will be zero up until 1994, when PROCAMPO was introduced. A priori, we expect a positive effect on the rate of adoption via a relaxation of the liquidity constraint. In addition, we include a dummy variable that equals one if the farmer was the recipient of other government support specifically targeting cattle ranching, including credits and subsidies, at any time prior to planting pasture, and zero otherwise. To the extent that such support increases profitability and reduces startup costs, it is expected to positively affect the hazard of adoption.

Size of landholding. We hypothesize that households operating larger farms will be more likely to adopt at any given time period. The threshold modeling tradition was initiated with a study that found larger farms more likely to adopt mechanical harvesters (David 1969). The core concept is that larger production units are more easily able to spread out the fixed costs of adoption. To accommodate nonlinear effects, we include both the size of the landholding, a static variable measured in hectares, and its square.

Biophysical attributes (1): average rainfall. We hypothesize that greater rainfall (measured as a fixed 18-year average) will increase expected profitability and thus will hasten adoption. Cattle are highly water dependent. They need to drink 50–70 liters on hot days when temperatures rise to 95–100 °F.[10] We measure rainfall in millimeters, which ranges from 934 to 1,274 mm in our sample. During dry spells, ranchers may have to undertake expensive efforts (in terms of labor or cash) to see that their herd's water requirements are met, for example by paying for a tanker truck to deliver water. More rainfall decreases the need for such costly efforts.

Biophysical attributes (2): soil quality. Soil quality is captured by a static dummy variable indicating the predominance of rendzina and other mollisols, which are distinguished from the low-lying, seasonally inundated vertisols that cover much of the region. We have no prediction as to its effect on cattle adoption. On the one hand, crop production is more dependent on having soil of good quality. From this perspective, bad soil quality would reduce the value of alternative uses and might induce farmers to grow pasture grasses and adopt cattle ranching. On the other hand, good soil quality might well be associated with greater profitability in crop production, which could provide the farmer the means to cover the startup costs of cattle ranching.

Educational attainment. We hypothesize that increasing educational attainment will positively affect the rate of adoption. Greater education, measured as a fixed value recorded at the time of the interview, may speed learning and may indicate an ability to achieve a higher level of mastery of a new technology, thus increasing expected profits.

Age of household head. We use the changing age of the household head as a proxy for location along different points in the household life cycle. Following the life-cycle theory of smallholder agricultural development (Walker et al. 2002), our null hypothesis is that the probability of adoption increases with age of the household head to a point and decreases thereafter. To capture this nonlinearity, both the variable age and its square are included in the model.

Geographic considerations. A priori, we suspect that greater distance from markets will slow the rate of adoption of cattle ranching, as it may increase the cost of learning and acquiring inputs. Ceteris paribus, greater distance would increase the cost of accessing the market. Location in space has been a consistent theme in the literature on diffusion going back to Rogers's early work on adoption of hybrid corn (1962). Rogers found that adoption was slower in areas father from away from population centers. To account for location, we include a set of dummies that indicate the village of residence. The effect of intravillage location is captured by the distance, measured in walking minutes, from the farmer's plot to his home in the village. We also develop a set of dummy variables for the state from which the household head migrated before settling in the SY, to control for state-of-origin effects. Two of the main states of origin for residents of the SY—Veracruz and Tabasco—are important in the Mexican national cattle sector, and thus we hypothesize that these variables will positively affect the probability of adoption.

Omitted variables. In the framework we have developed, expected profits, fixed costs of adoption, and liquidity constraints play central roles. Although we include a number of variables that afford reasonably broad coverage of these influences, the possibility of omitted variable bias can never be completely ruled out. Of particular concern is the question of whether we can identify the effect of the stock of prior adopters as distinct from the effects of other exogenous shifts over time that sweep through our sample of farmers. It may be the case, for example, that certain villages benefited from continuing (and unobserved) government support, with the consequence that farmers within these villages have behaved similarly in deciding to adopt pasture. We may thus falsely ascribe the adoption effect to learning, when, in fact, the government support was the driving force. Likewise, the results may be biased by what Manski (1993) has termed contextual effects: if farmers in the same network have similar skills, preferences for risk, or other unob-

[10] Personal communication, Eliseo Alcacar Ek, August 26, 2004 (Zoh Laguna). Personal communication, Carlos Riviera Echeverria, October 2, 2004 (Chan Laguna).

TABLE 2
Proportional Hazard Model Results

	Model 1	Model 2
Village network	1.051 (5.260)***	1.137 (5.130)***
Village network squared		0.999 (− 3.180)***
Government inducement	2.712 (2.750)***	2.293 (2.210)**
Prior years of chili cultivation	1.112 (2.650)***	1.103 (2.430)**
Hectares in PROCAMPO	1.005 (0.130)	1.008 (0.250)
Good soil	1.455 (1.190)	1.572 (1.420)
Rainfall	1.014 (2.560)**	1.013 (2.450)**
Distance from home to parcel	1.035 (1.180)	1.020 (0.660)
Landholding	1.008 (1.470)	1.043 (2.260)**
Landholding squared		1.000 (− 1.830)*
Age of head	1.020 (1.130)	1.223 (2.410)**
Age of head squared		0.998 (− 2.190)**
Education of head	1.082 (1.760)*	1.105 (2.000)**
State of origin		
Campeche	1.750 (0.820)	2.101 (1.050)
Chiapas	1.779 (0.900)	1.924 (0.990)
Tabasco	4.393 (1.950)*	7.084 (2.390)**
Veracruz	2.404 (1.540)	2.400 (1.350)
Chi-square village-trend interactions	26.760	34.040**
Log pseudolikelihood	–301.523	–289.890
Wald	206.120***	217.710***
Number of observations	2,816	2,816

Note: Z-Statistic in parentheses.
*$p < 0.1$; **$p < 0.05$; ***$p < 0.01$.

served attributes, this will induce a correlation among adoption choices of farmers in the same network even if there is no causal relationship (Bandiera and Rasul 2006).

Two features of the specification ameliorate concerns about incorrect inferences that would otherwise emerge from such effects. First, recognizing that the correlation caused by contextual effects is positive, Bandiera and Rasul (2006, 897) note that the nonlinearity built into the network variable, if verified, provides some assurance that these effects are not driving the results. Second, the specification further mitigates against omitted variables by including the interaction of each village dummy with a time trend, which serves to capture the influence of unobserved village-level determinants that monotonically vary over time. These features notwithstanding, the caveat still applies that there may be unobserved individual-level influences that are correlated with the network variable.

V. ECONOMETRIC RESULTS

Table 2 presents the hazard ratios from two model specifications that are distinguished by the functional form of select explanatory variables. In Model 1 all variables enter linearly, while in Model 2 select variables are specified as a quadratic function following from the theoretical considerations outlined above. Overall, Model 2 provides a better fit to the data, as evidenced by the highly significant likelihood ratio statistic (likelihood ratio $chi^2 = 23.27$, $p < 0.0001$). Moreover, the increased flexibility of this model yields several additional coefficients that are statistically significant. We therefore reference this model in interpreting the results. To facilitate interpretation, we transform the coefficients as hazard ratios by taking their exponent, which gives the proportional change in the hazard rate due to a one-unit change in an explanatory variable.

Specification Tests

Before discussing the estimates, we conduct some specification tests to gauge the validity of the model. A key assumption is that there exists a proportional hazard rate that is dependent only on time and common to all individuals in the population. Grambsch and Therneau (1994) have developed a test for this assumption based on the scaled Schoenfeld residuals (s_j^*), with j indexing each failure time. They show that $E(s_j^*) + \hat{\beta} = \beta_j(t)$, where $\hat{\beta}$ is the estimated coefficient from the Cox model. The proportional hazards assumption restricts $\beta_j(t) = \beta$ for all t, which further implies that a plot of $\beta_j(t)$ over time will have a slope of zero. The null hypothesis is a zero slope, the rejection of which would call the proportional hazard assumption into question. Neither the global test nor the test for any particular covariate produces rejection of the null hypothesis.

We do another overall specification test using the Martingale residuals, or rather the Martingale residuals scaled to be symmetric about zero because the untransformed residuals are skewed and more difficult to interpret. We plot the transformed Martingale residuals (also called deviance residuals) against time and find no systemic patterns or obviously aberrations that would lead us to question the model's validity.

A final robustness check involves comparing the results of our proportional hazard model with the results of parametric survival models, the regressionlike approaches that vary based on their distributional assumptions. We estimated models based on the assumption of exponential, Weibull, lognormal, and log-logistic distributed errors, and in each case found that the significant variables matched those in our proportional hazard model.

Coefficient Estimates

Turning to the coefficient estimates, we begin by noting that the coefficients of the village network and its square confirm the predictions of the theoretical model: increases in this variable increase the hazard of adoption but at a decreasing rate, thereby corroborating the findings of Bandiera and Rasul (2006).[11]

[11] Following these authors, we also explored specifications in which the effect of the village network depends on the traits of the farmer through the inclusion of interaction terms. We found no evidence in support of statistically significant differential effects.

By referencing the coefficient estimates (i.e., the log of the hazard ratios), the peak influence can be calculated to occur when roughly 64.1% of village households have adopted. The timing of the introduction of pasture into the land use portfolio is thus significantly correlated with the existing share of farmers who plant pasture, which is suggestive of a role for social spillover effects in driving land use change.

With respect to the remaining statistically significant estimates, all are consistent with our a priori hypotheses. As with the village network, the age of the household head and the size of the landholding both have nonlinear effects that initially increase the hazard rate. Likewise, education, prior years of chili cultivation, government inducements, and rainfall all have positive effects on the hazard rate. In the case of education and chili cultivation, the effects are of roughly the same magnitude, with each additional year increasing the hazard rate by about 1.1. The rainfall variable has a slightly lower magnitude, suggesting that each millimeter increase increases the hazard by 1.01. A more pronounced effect is given by the government inducement dummy: households that have received inducements have 2.29 times the likelihood of planting pasture as those that have not. The other program variable, PROCAMPO, is insignificant, a somewhat surprising result given other research showing that these payments are an important determinant of the area cultivated (Klepeis and Vance 2003; Schmook and Vance 2009).

Turning to state-of-origin effects and village effects, we expected that household heads from Tabasco or Veracruz would be more likely to adopt, as these are major cattle-producing states. The Tabasco variable is significant as expected, though not Veracruz. Finally, a chi square test of the village dummies and their interaction with the time trend indicates that these are jointly significant.

Exploring the Baseline Hazard and Survival Functions

The baseline hazard function $\lambda_0(t_i)$ is defined at every time t that a failure occurs (every time adoption of cattle ranching takes

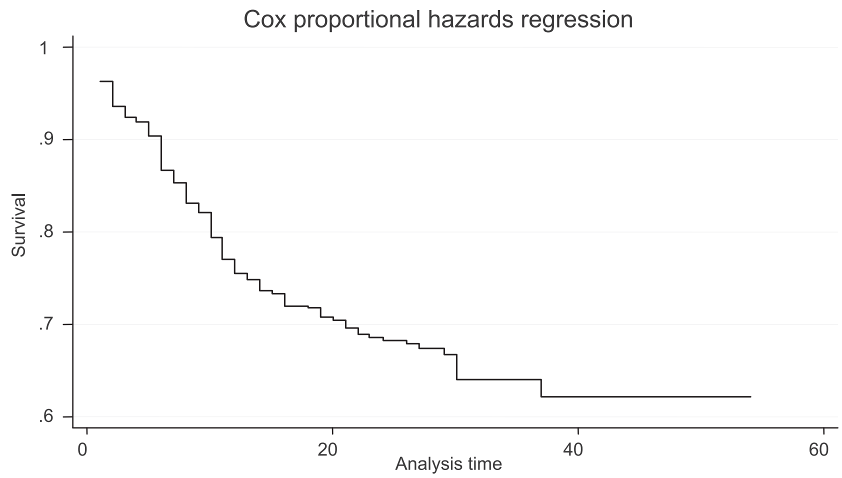

FIGURE 2
The Survival Function

place in our model). The baseline hazard is undefined (or defined as zero) at other times. A counterpart to the baseline hazard function is the baseline survival function, which is defined as the probability of surviving (i.e., not adopting cattle ranching) just beyond time *t* conditional on surviving up to and including time *t*. Unlike the hazard function, the survival function is defined at all values of *t*. It decreases each time a failure occurs, but if no failure occurs in a given time period, the survival function remains at the same level as the time of the last failure. Below we plot the survival function for our model (Figure 2) and the smoothed hazard function (Figure 3), both calculated at the mean value for each covariate.

The main feature of the hazard function is that it increases to a point, 10 years after household formation, and falls thereafter. Interestingly, this result is consistent with the story that comes out of the imitation modeling literature: during a period of early adoption and takeoff there are increasing marginal rates of adoption, and, after some peak point, there begin to be declining marginal rates of adoption. We must be a little bit careful, however, in making such an analogy. The above survival and hazard functions are defined in terms of household time; time is measured with the year of household formation as time zero. Imitation models typically are defined with respect to a population over historical time. If all households were formed at the same time, the difference between the two time frames would be greatly reduced.

Why might it be that the baseline hazard rate increases to a point and decreases thereafter? Since we are dealing with an individual's hazard rate in isolation, we cannot rely on the epidemic-type explanation that underpins imitation models. Consider this alternative: Successful adoption of cattle ranching may be facilitated by a household's ability to take advantage of random opportunities. Over time, more such opportunities are likely to present themselves, and thus the probability of adopting increases. However, after some point, individuals that have not adopted include mostly those who are inherently less motivated to adopt, less capable, or less lucky. Thus, after some point, the marginal rate of adoption declines.

In fact, the hazard function does not decline continuously after year 10. The nonparametric baseline hazard jumps around substantially. This is evident in the plot of the survival function, which is not smoothed and gives a better idea of the baseline hazard in any particular time period. Surveying the survival function in Figure 2, the largest drop (corresponding to a large baseline hazard) in

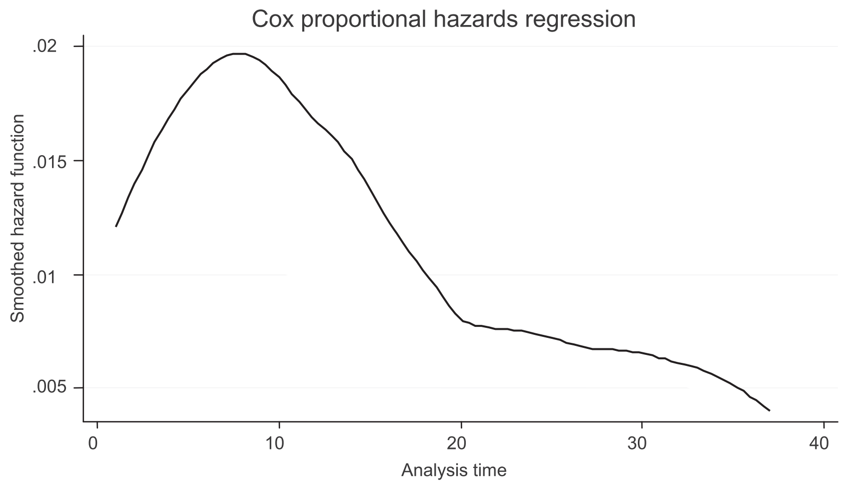

FIGURE 3
Smoothed Hazard Function

the survival curve is seen to take place at year 30. There is another large drop at year 37. We reviewed the three cases that correspond to these years (two cases failed at year 30, and one at year 37). We found no obvious reason to exclude them and thus choose to accept this irregularity rather than arbitrarily dropping the cases from the estimation.

VI. DISCUSSION AND CONCLUSION

We have developed a framework for modeling diffusion of cattle ranching in which the household decision on whether to begin cattle ranching is driven by the incentives for adoption (relative profitability), the constraints these decision-making agents face, and the social and institutional structure within which these agents operate. Most importantly, we sought to capture the opportunity for learning from others with a measure of the strength of the social network—the percentage of adopters in the village. Indeed, we find that a higher percentage of adopters during the previous year increases the chance of adoption in the next year up to the point when 64% of the village has adopted, after which the effect is negative. We also find that the hazard of adoption is increased by greater average rainfall, government inducements, and larger farm size. Government inducements play a crucial role in affecting the hazard of adoption, especially subsidies directly promoting cattle ranching, which help overcome the startup costs. A central factor in a household's decision to adopt is its ability to develop the necessary infrastructure, which requires a substantial cash investment absent government assistance. We found one significant time-varying measure in this vein, the sum of prior years that the household has grown jalapeño chili peppers, which is positively associated with a higher hazard of adoption of cattle ranching. We have also found evidence that more educated household heads are more likely to adopt.

What does this work mean for our understanding of the future of the cattle sector and trends in deforestation in the SY, and in particular the potential for a hollow frontier in the region? We have established why cattle ranching has such a great potential to transform the landscape of the SY. The activity is less affected by the soil and labor constraints that substantially limit the area deforested for use by crop farmers. We have reported our finding that the expansion of pasture for cattle has driven recent deforestation even as the area devoted to crop cultivation has diminished. We have traced the trend toward increasing adoption of the activity by households that had not previously practiced cattle ranching. Our findings and macrotrends in the region suggest that the spread of cattle ranching and associated deforestation for planting of pasture will continue.

Direct evidence of this comes from the response to a question asked of those who have yet to adopt cattle ranching if they plan to do so, which found remarkable interest: 24 of 71 who had never attempted cattle ranching told us they have specific plans to begin within a year after. Another 28 of 71 said they hope to start cattle ranching, though their plans were less specific and sometimes dependent on receiving government assistance. Only 19 households expressed no interest in entering the cattle sector.

What do our modeling exercise and observations about trends in the region tell us about the potential for continued diffusion and expansion of pasture for cattle? Some notable macrotrends in the SY are increasing per capita income, better access to support from government and nongovernment programs, improved transportation and commercial links to outside markets, and migration to the United States for higher paying jobs. While poverty remains endemic in the region, perhaps the most severe in Mexico, some improvement is taking place. Household incomes are rising, albeit slowly and unevenly. Our modeling results, consistent with our direct questioning on motives for having begun or not yet begun cattle ranching, suggest that over time a relaxation in the income constraint will spur increased adoption of cattle ranching.

An as yet unanswered question is how migration and increasing nonfarm opportunities will affect adoption of cattle ranching and the deforestation rate. To the extent that migration provides a boost to incomes and makes it easier for these households to cover the startup costs associated with cattle ranching, migration could facilitate the diffusion process. This would be consistent with a hollow frontier scenario in which the spread of extensive, low-value cattle ranching coincides with the decreasing population density. Such an outcome has been observed in several other Latin American contexts, including Columbia (Ortiz 1984) and Panama (Sloan 2007).

While it is still too early to say whether the SY will follow this trajectory, there are some indications of a hollow-frontier dynamic taking hold as the diffusion of pasture progresses. As documented by Radel, Schmook, and Chowdhury (2010), between 1997 and 2003 there was an increase in the participation of households in off-farm labor accompanied by a significant decrease in crop cultivation, with the area planted in maize and chili peppers falling by 27% and 28%, respectively. At the same time, however, not only did the number of farmers planting pasture increase, but so too did the area planted, rising by an average of 15%. Taken together, these trends could be viewed as part of a rational frontier household's strategy of optimal use of resources and risk management, including diversification of the household's economic portfolio to include both migration (employment outside the region) and cattle ranching.

Recent history has seen improvement of the region's transportation system, and this process continues (e.g., during our field work the federal government continued upgrades to the main highway that bisects the region). Better transportation links will make it easier over time for cattle ranchers to access distant markets. A related trend is improved connection to external markets; neighborhood effects mean that these marketing pioneers, who are establishing the pathways and practices for successful marketing, will make it easier for others to follow.

Government programs supporting expansion of the cattle sector continue to be strong and are likely to continue as such at least for the next few years. New policies subsidizing fence building and providing a per animal subsidy for cattle owners were put in place in the years immediately preceding fieldwork (Busch 2006). These policies coexist with many programs aimed at intensifying and limiting land use, such as (1) subsidies and extension services promoting "green fertilizers," nitrogen-fixing legumes that are intended to extend soil fertility; (2) subsidized tractor use; and (3) promotion of non–land use based economic activities such as organic honey production and ecotourism.

The future course of land use and development in the SY will depend on the outcome of the conflict between forces in favor of exploitation of the land for the benefit of the local people and forces in favor of forest conservation and sustainable development. The voices for sustainable development are steadily growing stronger. Though it has long been practiced and continues to be, the cutting of primary forest without prior approval is technically illegal throughout Mexico under Article 27 of the Mexican Constitution, which defines primary forest as public property. Though the provision had long been ignored, awareness of the prohibition is growing, as is enforcement. During our time in the field a farmer in one village was incarcerated for cutting down primary forest. This is just one instance of the many examples of increasing attention and pressures for conservation and sustainability in the SY.

The challenge for policy makers will be to foster conservation and sustainability in a way that also improves the lives of the local residents. Cutting subsidies for cattle ranching is a necessary but not sufficient step. How to provide the necessary positive incentives for households facing poverty at the forest frontier? We suggest two courses of action based on our findings.

First, payments for carbon sequestration, or for environmental goods and services more broadly, could be a promising avenue. The recently concluded Bali meeting of the United Nations Framework Convention on Climate Change provides some indication that payments for avoided deforestation will be a part of the agreement that will follow the Kyoto Protocol when it expires in 2012.[12] Our data show that cattle ranching as practiced in the SY provides a relatively modest return, approximately $50 per hectare in 2003 U.S. dollars (Busch and Geoghegan 2010), implying that farmers could be dissuaded from planting pasture at relatively low cost. Second, such payments should be accompanied by information campaigns that educate farmers on the environmental benefits of allowing land under agriculture to revert to forest rather than planting pasture. Given the role of social networking in the diffusion of agricultural technologies uncovered here, policy makers should endeavor to harness information flows among the region's farmers by directing such campaigns to strategically situated villages where cattle-related commerce transpires.

Together, environmental service payments and targeted dissemination of information on the benefits from forest preservation could offer hope for simultaneously achieving improved management of the region's important forestland and economic progress for the region's mostly impoverished residents.

[12] For an overview of the Bali meeting see the International Institute for Sustainable Development's Earth Negotiations Bulletin: Summary of the Thirteenth Conference of Parties to the UN Framework Convention on Climate Change," December 18, 2007, available at www.iisd.ca/climate/cop13/.

Acknowledgments

We gratefully acknowledge assistance received from Michael Hanemann, Lee Friedman, Billie L. Turner II, Jacqueline Geogehegan, Birgit Schmook, Francisco Gurri, Juan Manuel Pat Fernández, Eric Keys, Hans Vester, Jeffrey LeFrance, Harald Tauchmann, and Michael Turner. Thanks as well to our field team and to the residents of the southern Yucatan, especially Baltazar González Zapata and Eliseo Ek Alocer. Funding for this research was provided by the Global Change Education Program (a program of the U.S. Department of Energy), and the University of California's Institute for Study of Mexico and the United States. This research was conducted in cooperation with the Sothern Yucatan Peninsular Region project involving Clark University, the University of Virginia, El Colegio de la Frontera Sur, and Harvard University; the project's principal sponsors have been the NASA-LCLUC (Land Cover and Land Use Change) program (NAG5-6046, NAG5-11134, and NNG06GD98G), Center for Integrated Studies of the Human Dimensions of Global Environmental Change, Carnegie Mellon University (NSF SBR 95-21914), and NSF-Biocomplexity (BCS-0410016). Colin Vance was additionally supported by a grant from the Collaborative Research Center "Statistical Modelling of Nonlinear Dynamic Processes" (SFB 823) of the German Research Foundation (DFG).

References

Allison, Paul D. 1995. *Survival Analysis Using the SAS System: A Practical Guide.* Cary, NC: SAS Institute, Inc.

Bandiera, Oriana, and Imran Rasul. 2006. "Social Networks and Technology Adoption in Northern

Mozambique." *Economic Journal* 116 (514): 869–902.

Bardhan, Pranab. 1999. *Development Microeconomics.* Oxford, UK: Oxford University Press.

Besley, Timothy J., and Anne Case. 1994. "Diffusion as a Learning Process: Evidence from HYV Cotton." Discussion Paper 174. Princeton, NJ: Princeton University, RPDS.

Brothers, Timothy S. 1997. "Deforestation in the Dominican Republic: A Village-Level View." *Environmental Conservation* 24 (3): 213–23.

Busch, Christopher B. 2006. "Deforestation in the Southern Yucatán: Recent Trends, Their Causes, and Policy Implications." Ph.D. diss., University of California, Berkeley.

Busch, Christopher B., and Jacqueline Geoghegan. 2010. "Labor Scarcity as an Underlying Cause of the Increasing Prevalence of Deforestation due to Cattle Pasture Development in the Southern Yucatán Region." *Regional Environmental Change* 10 (3): 191–203.

Conley, Timothy G., and Christopher R. Udry. 2010. "Learning about a New Technology: Pineapple in Ghana." *American Economic Review* 100 (1): 35–69.

Cox, D. R. 1972. "Regression Models and Life-Tables (with discussion)." *Journal of the Royal Statistical Society Series B* 34 (2): 187–220.

Cox, D. R., and David Oakes. 1984. *Analysis of Survival Data.* London: Chapman and Hill.

David, Paul A. 1969. *A Contribution to the Theory of Diffusion.* Memorandum No. 71. Stanford, CA: Stanford Center for Research in Economic Growth.

Deaton, Angus. 1997. *The Analysis of Household Surveys: A Microeconomic Approach to Development Policy.* Baltimore, MD: John Hopkins Press.

DeFries, Ruth S., Gregory P. Asner, and Richard A. Houghton. 2004. "Trade-Offs in Land-Use Decisions: Towards a Framework for Assessing Multiple Ecosystem Responses to Land-Use Change." *Geophysical Monograph Series* 153 (1): 1–9.

Durand, Leticia, and Elena Lazos. 2004. "Colonization and Tropical Deforestation in the Sierra Santa Marta, Southern Mexico." *Environmental Conservation* 31 (1): 11–21.

Efron, Bradley. 1977. "The Efficiency of Cox's Likelihood Function for Censored Data." *Journal of the American Statistical Association* 72 (359): 557–65.

Feder, Gershon, Richard E. Just, and David Zilberman. 1985. "Adoption of Agricultural Innovations in Developing Countries: A Survey." *Economic Development and Cultural Change* 33 (2): 255–98.

Food and Agricultural Organization of the United Nations (FAO). 2006. *Livestock's Long Shadow: Environmental Issues and Options.* Rome: FAO. Available at www.fao.org/docrep/010/a0701e/a0701e00.HTM.

Foster, Andrew D., and Mark R. Rosenzweig. 1995. "Learning by Doing and Learning from Others: Human Capital and Technological Change in Agriculture." *Journal of Political Economy* 103 (6): 1176–1209.

Grambsch, Patricia M., and Terry M. Therneau. 1994. "Proportional Hazards Tests and Diagnostics Based on Weighted Residuals." *Biometrika* 81 (3): 515–26.

Griliches, Zvi. 1957. "Hybrid Corn: An Exploration in the Economics of Technical Change." *Econometrica* 25 (4): 501–22.

———. 1958. "Research Costs and Social Concerns: Hybrid Corn and Related Innovations." *Journal of Political Economy* 66 (5): 419–31.

Hecht, Susanna B. 1985. "Environment, Development, and Politics: Capital Accumulation and the Livestock Sector in Eastern Amazonia." *World Development* 13 (6): 663–84.

Holston, James. 1991. "The Misrule of Law: Land and Usurpation in Brazil." *Comparative Studies in Society and History* 33 (4): 695–725.

Jones, Jeffrey R. (1989). "Human Settlement of Tropical Colonization in Central America." In *The Human Ecology of Tropical Lands Settlement in Latin America,* ed. Debra A. Schumann, and William L. Partridge. San Francisco: Westview Press.

Klepeis, Peter, and Rinku R. Chowdhury. 2001. "Institutions, Organizations, and Policy Affecting Land Change: Complexity Within and Beyond the Ejido." In *Integrative Land Change Science and Tropical Deforestation in the Southern Yucatán: Final Frontiers,* Clarendon Lectures in Geography and Environmental Studies, ed. B. L. Turner II, Jacqueline Geoghegan, and David R. Foster. Oxford, UK: Oxford University Press.

Klepeis, Peter, and Colin Vance. 2003. "Neoliberal Policy and Deforestation in Southeastern Mexico: An Assessment of the PROCAMPO Program." *Economic Geography* 79 (3): 221–40.

Lin, D. Y., and L.-J. Wei. 1989. "Robust Inference for Cox Proportional Hazards Model." *Journal of the American Statistical Association* 84: 1074–79.

Manski, Charles F. 1993. "Identification of Endogenous Social Effects: The Reflection Problem." *Review of Economic Studies* 60 (3): 531–42.

Masera, Omar R., María J. Ordóñez, and Rodolfo Dirzo. 1997. "Carbon Emissions from Mexican Forests: Current Situation and Long-Term Scenarios." *Climate Change* 35 (3): 265–95.

Mather, A. S., and C. L. Needle. 1998. "The Forest Transition: A Theoretical Basis." *Area* 30 (2): 117–24.

Munshi, Kaivan. 2004. "Social Learning in a Heterogeneous Population: Technology Diffusion in the Indian Green Revolution." *Journal of Development Economics* 73 (1): 185–213.

———. 2008. "Information Networks in Dynamic Agrarian Economies." In *Handbook of Development Economics,* Vol. 4, ed. T. Paul Schultz, and John Strauss. Amsterdam: Elsevier.

Ortiz, Sutti. 1984. "Colonization in the Colombian Amazon." In *Frontier Expansion in Amazonia,* ed. Marianne Schmink and Charles Wood. Gainesville: University of Florida Press.

Radel, Claudia, Birgit Schmook, and Rinku R. Chowdhury. 2010. "Agricultural Livelihood Transition in the Southern Yucatán Region: Diverging Paths and Their Accompanying Land Changes." *Regional Environmental Change* 10 (3): 205–18.

Robalino, J. A., and A. Pfaff. 2009. "Contagious Development: Neighbor Interactions in Deforestation." Unpublished manuscript. EfD Initiative–CATIE, Turrialba, Costa Rica.

Rogers, Everett M. 1962. *Diffusion of Innovations,* 1st ed. New York: Free Press.

Rudel, Thomas K., Diane Bates, and Rafael Machinguiashi. 2002. "A Tropical Forest Transition? Agricultural Change, Out-migration, and Secondary Forests in the Ecuadorian Amazon." *Annals of the Association of American Geographers* 92 (1): 87–102.

Rudel, Thomas K., Oliver T. Coomes, Emilio Moran, Frederic Achard, Arild Angelsen, Jianchu Xu, and Eric Lambin. 2005. "Forest Transitions: Toward a Global Understanding of Land Use Change." *Global Environmental Change* 15 (1): 23–31.

Rutsch, Mechthild. 1980. "Acerca de la Ganaderia Capitalista en Mexico." *Nueva Antropologia* 4 (13–14): 147–86.

Sader, Steven A., and Armond T. Joyce. 1988. "Deforestation Rates and Trends in Costa Rica." *Biotropica* 20 (1): 11–19.

Schmook, Birgit, and Colin Vance. 2009. "Agricultural Policy, Market Barriers, and Deforestations: The Case of Mexico's Southern Yucatán." *World Development* 37 (5): 1015–25.

Sloan, Sean. 2007. "Fewer People May Not Mean More Forest for Latin American Forest Frontiers." *Biotropica* 39 (4): 443–46.

Sunding, David, and David Zilberman. 2001. "The Agricultural Innovation Process: Research and Technology Adoption in a Changing Agricultural Sector." In *Handbook of Agricultural Economics,* Vol. 1, ed. Bruce L. Gardner, and Gordon Rausser. Amsterdam: Elsevier Science.

Toledo, Victor M.. 1991. "Ecología y autosuficiencia alimentaria en México. *Agroecología y Desarrollo* 1 (1): 52–5.

Turner, B. L., II, Sergio Cortina Villar, David Foster, Jacqueline Geoghegan, Eric Keys, Peter Klepeis, Deborah Lawrence, Pedro Macario Mendoza, Steven Manson, Yelena Ogneva-Himmelberger, Audrey B. Plotkin, Diego Pérez Salicrup, Rinku Roy Chowdhury, Basil Savitsky, Laura Schneider, Birgit Schmook, and Colin Vance. 2001. "Deforestation in the Southern Yucatán Peninsular Region: An Integrative Approach." *Forest Ecology and Management* 154 (1): 343–70.

Turner, B. L., II, Jacqueline Geoghegan, and David Foster, eds. 2004. *Integrative Land Change Science and Tropical Deforestation in the Southern Yucatán: Final Frontiers*. Clarendon Lectures in Geography and Environmental Studies. Oxford, UK: Oxford University Press.

Vance, Colin, and Jacqueline Geoghegan. 2002. "Temporal and Spatial Modeling of Tropical Deforestation: A Survival Analysis Linking Satellite and Household Survey Data." *Agricultural Economics* 27 (3): 317–32.

Walker, R. T. 1993. "Deforestation and Economic Development." *Canadian Journal of Regional Science* 16 (3): 481–97.

Walker, Robert, Stephen Perez, Marcellus Caldas, and Luiz G. Teixeira Silva. 2002. "Land Use and Land Cover Change in Forest Frontiers: The Role of Household Life Cycles." *International Regional Science Review* 25 (2): 169–99.