Human Organization, Vol. 67, No. 4, 2008

0018-7259/08/040384-13$1.70/1

Cash Cropping, Farm Technologies, and Deforestation: What are the Connections? A Model with Empirical Data from the Bolivian Amazon

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Research suggests that cash cropping is positively associated with deforestation. We use three-year data (2000-2002, inclusive) from 493 households to estimate the association between cash cropping rice and deforestation. Doubling the area sown with rice is associated with a 26-30 percent increase in the area of forest cleared during the next cropping season. We simulate the changes in rice cultivation to reach a daily income level of $1/person from cash cropping rice. We find that within 10 years: (1) the amount of deforestation would triple, (2) work requirements would exceed household's labor availability, and (3) fallows duration would decrease two-fold. To avoid the increase of deforestation from cash cropping requires increasing productivity, diversification of income sources, or both.

Key words: Latin America, Bolivia, deforestation, cash crop, poverty alleviation, farm technology

Introduction

Awareness of the many ecological services provided by tropical forests (Costanza et al. 1997) and the rapid increase in tropical deforestation has put forests at the center stage of the policy debate between developers, conservationists, and policymakers. Researchers have studied many of the factors influencing deforestation, such as the opening of new roads (Chomitz and Gray 1996; Reid 2001), property rights (Alston, Libecap, and Mueller 2000; Deacon 1999; Godoy, Kirby, and Wilkie 2001), the spread of cash cropping (McMorrow and Talip 2001), slash-and-burn agriculture, cattle ranching, and logging (Hecht and Cockburn 1989; Palm et al. 2005). Research suggests that the drivers of deforestation interact in complex ways (Angelsen and Kaimowitz 1999).

Because of the complexity of the issue, site-specific variability, and the lack of reliable empirical information about the causes of deforestation, there is little consensus as to which mechanisms best explain deforestation (Kaimowitz and Angelsen 1998). A lack of empirical information hinders our understanding of deforestation. Kaimowitz and Angelsen (1998) reviewed 146 econometric models of deforestation and found that 24 percent relied on simulations and 23 percent drew on theoretical models that included no empirical data. Furthermore, among the 53 percent of the studies based on empirical data, 38 drew on secondary, national-level data. Only nine of the models reviewed (6% of total) used household-level empirical data. The authors suggest that future studies of the causes of deforestation should focus on household and regional-level data, with a strong micro-level empirical base (Kaimowitz and Angelsen 1998:99). Since the publication of the review by Kaimowitz and Angelsen, another excellent household-level study of deforestation has appeared (Rudel 2005).

This study has two aims. In the first part, we draw on household-level data from the Tsimane', a horticultural and

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foraging society of native Amazonians in Bolivia, to assess how cash cropping by smallholders affects neotropical deforestation. We focus on clearing of fallow and old-growth forest because previous research suggests that both forest types harbor substantial biological diversity (Finegan 1996; Silver, Brown, and Lugo 1996; Smith et al. 1999). In the second part of the paper, we use data in a needs-based simulation to explore the consequences of the rural poor using cash crops to escape poverty. We focus on the consequences of household-level decisions to deforest for the total area of forest cleared, for household labor requirements, and for the duration of the fallow. We pay special attention to fallow duration because previous research suggests that increased land scarcity reduces the length of fallow (Coomes, Grimard, and Burt 2000).

This work contributes to the debate on the causes of deforestation in several ways. First, we use household-level data, which is relatively rare in studies of deforestation (Kaimowitz and Angelsen 1998). Second, we document deforestation by indigenous peoples. Indigenous peoples do not account for a large share of deforestation, but this share could grow as indigenous people become more integrated into the market economy (Godoy 2001) and their population swells (Picchi 1991). Third, we contribute to the debate on the effects of technological innovations in agriculture to deforestation. The results of the simulations could help formulate recommendations as to the type of technologies needed to reconcile development and conservation of tropical forests.

Cash Cropping, Farm Technologies, and Deforestation

While many studies address causes of deforestation, few use primary data to focus on the effects of cash cropping. The empirical literature available often focuses on the impact of cash cropping on deforestation through the introduction of new farm technologies (Angelsen and Kaimowitz 2001; McMorrow and Talip 2001; Pendleton and Howe 2004).

Some of the evidence suggests that cash cropping increases deforestation. For example, Dearden (1995) found that in Thailand, intensification of cash cropping of cabbage increased deforestation because cabbage had a low value compared with opium, which it was replacing. In a household-level study in Cameroon, Mertens and colleagues (2000) found that deforestation increased as the marketing of food crops increased. Other researchers suggest that cash cropping does not necessarily contribute to deforestation. For example, Tungittiplakorn and Dearden (2002) also found that cash cropping cabbage and carnations in Thailand reduced pressure on forests because the new cash crops required less land than traditional crops, and therefore allowed more people per unit of land. Similarly, Perz (2004) found that raising rural income through agricultural diversity in forest frontiers did not necessarily reduce forest cover.

Part of the debate on the effects of cash cropping on tropical forests clearing relates to the use of new farm technologies. A common assumption is that technological improvements in agriculture would decrease deforestation because an increase in production per unit area would reduce the farmers' need to keep clearing new lands (Holden 1993; Jones et al. 1995; Palm et al. 2005). However, some empirical studies suggest that new agricultural technologies contribute to environmental degradation and deforestation (Godoy 2001; Humphries 1993; Marquette 1998). For example, Humphries (1993) found that agricultural intensification among Yucatec Maya smallholders increased sedentary production, and heightened reliance on chemicals, with negative consequences for the environment. In the Ecuadorian Amazon, Marquette (1998) found that improvements in human welfare of settlers in the agricultural frontier were related to economic activities that increased the area of land cleared.

A third group of authors suggests that technological improvements might produce ambiguous results, depending on the type of agricultural technology used (Angelsen and Kaimowitz 2001). For example, Pichón and colleagues (2002) found that in the Ecuadorian Amazon, farmers in agricultural frontiers adopted a low-intensity strategy for coffee production, which generated less forest clearing. However, farmers who could afford it specialized in raising cattle, which increased both income and forest clearing.

In sum, prior studies on the impact of cash cropping and new farm technologies on deforestation have produced ambiguous results.

Materials and Method

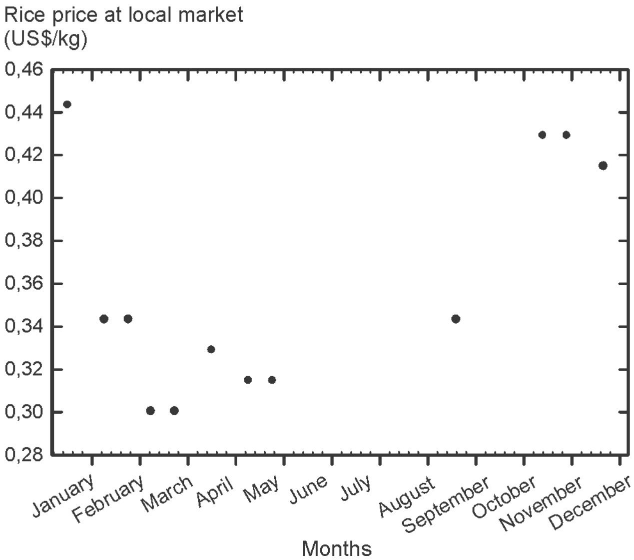
Tsimane' Agriculture

The Tsimane' live in the lowlands of Bolivia, mostly along the Maniqui and Apere rivers in the department of Beni. Detailed ethnographies of the Tsimane' can be found in recent dissertations and books (Byron 2003; Chicchon 1992; Daillant 2003; Ellis 1996; Huanca 2007; Reyes-García 2001).

Tsimane' are hunters who also practice slash-and-burn agriculture to cultivate upland rice, maize, manioc, and plantains as main staples. They also plant a variety of less important crops, such as sugar cane, peanuts, sweet potatoes, ahipa, and citrus (Huanca 1999; Piland 1991; Vadez et al. 2003). Although Tsimane' have remained foragers and depend on forest resources, they are becoming increasingly dependent on farming. Farm products account for more than half of the cash income of the Tsimane' (Reyes-García 2001).

The Tsimane' gather and farm their own land. Tsimane' land legally belongs to the entire ethnic group. In a typical village, houses are scattered around the school, and households usually farm around the village in a radius of about 2 kilometers. The mean nucleated area of a village measures about 1,250 hectares. Land availability per household depends on the number of households in the village. We found that villages had between 10 and 70 households, suggesting that each household has access to between 18 and 125 hectares of land.

Figure 1. Retail Rice Prices in San Borja, Bolivia, in 2002-2003



Tsimane' farming is extensive, and oriented to household consumption and sale. People usually abandon the plots after one or two cultivation cycles and clear another plot. In a recent study, we found that the market economy is influencing the traditional farming practices of Tsimane', but not in the expected direction. Unlike previous studies with native Amazonians (Godoy 2001), we found that Tsimane' integration in the market economy did not decrease the diversity of crops grown (Vadez et al. 2004). Households more integrated into the market economy cultivated more rice, a finding consistent with the increasing demand for rice in the region and with the increasing importance of rice in the household economy of the Tsimane'.

Tsimane' believe that all plants and animals were humans in mythical times, and that the gods converted some of the humans into today's animals and plants. Because Tsimane' believe that humans, animals, and plants share a common ancestry, they consider them their kin and have a reverential attitude toward the forest plants and animals (Huanca 2007).

The Importance of Rice

In Bolivia, the domestic demand for rice exceeds domestic supply (Comisión Europea 2000). The same situation occurs in the local market, where the rice supplied by local producers does not match demand. Part of the rice consumed comes from other regions of Bolivia, such as the department of Santa Cruz, or from abroad. Since rice demand is higher than supply, there are strong incentives to increase local rice production.

Jesuit missionaries introduced rice into the Tsimane' territory over 300 years ago (Perez-Diez 1983; Vadez et al. 2004). Because of this recent introduction, rice lacks the wide range of traditional beliefs associated with crops indigenous to the area, such as manioc (Huanca 2007). In the 1950s, missionaries introduced improved rice varieties together with manual sowing machines, technologies that are now widely used by the Tsimane'. Later, colonist farmers introduced herbicides and pesticides for use in rice farming, but even today few Tsimane' use those chemicals.

Tsimane' usually open farm plots between July and November, sow rice between August and December, and harvest rice during the rainy season, between January and April. Rice is both a staple and a cash crop and is cultivated on 60-80 percent of the surface of newly-opened fields (Vadez et al. 2004); the exact share depends on the degree of a household's integration to the market economy. Tsimane' sell rice and other farm products in the town of San Borja (population approximately 19,000), but they also sell the products to itinerant traders who ply the main rivers and roads of the area.

Insufficient rice supplies in the town of San Borja drive up the price of rice in the local market town (Figure 1). For example, the price in the local market was \$0.28/kg shortly after harvest in March 2002, and twice as high (\$0.48/kg) before the following harvest in January 2003. However, Tsimane' farmers do not take advantage of price fluctuations and sell most of their production shortly after the harvest, when prices reach their lowest levels.

Sampling and Data Collection

We collected information from the same households in 2000, 2001, and 2002. The total sample size reached 715 households in 18 Tsimane' villages; we interviewed 174 households in all three years, and 493 in at least two consecutive years. The surveys used a random sub-sample of 8-12 households per village. In this paper, we use data only from households for which we had repeated observations for at least two consecutive years. Our sampling strategy allowed us to reduce biases from possible reverse causality, at least in part, by regressing deforestation at time $n+1$ against explanatory variables during time n. Although we do not exclude the possible role of third variables having potentially an effect on both rice area cropped last year and today's deforestation, the procedure represents an improvement over earlier studies of deforestation that typically rely on contemporaneous cross-sectional information of outcome and explanatory variables.

To estimate the area of forest cleared, we asked the male household head to report the area of all plots from old-growth and fallow forests owned by the household during the last farming cycle and the type of forest cleared. Self-reported estimates matched closely the area cleared (Vadez et al. 2003). We proxied rice cultivation by asking the male household head about the area sown with rice. All measures of area under rice cultivation in the surveys reflected the rice area sown in the previous cropping season. We did not use cash earnings from the sale of rice as a proxy for rice cultivation because the volume of rice sale fluctuates over the year and the surveys

Table 1. Description and Summary Statistics of the Variables Measured in Surveys (2000-2002)

Variable	Definition	Mean	Sd	Obs.
Dependent				
Total clearing	Total area cleared per household equivalent[a], in hectares	0.266	0.273	493
Old-growth forest clearing	Area of old-growth forest cleared per household equivalent[a], in hectares	0.120	0.204	463
Explanatory				
Rice area	Total area planted with rice per household equivalent[a], in hectares	0.222	0.201	469
Walking time	Time to the nearest market town, in hours	9.85	10.22	470
Road access	Accessibility year round to the village with motor vehicle (0=no access; 1=access)	0.39	0.49	470
Cash income	Total household income in past two weeks from sales and wage labor, in US$.	32.01	61.06	472
Market dependence	Ratio of cash income/(cash income + consumption value of rice + maize + manioc)	0.313	0.304	466

[a] Area per household equivalent was calculated based on 4.2 adult equivalent per household (sd=1.82, n=493)

took place during three different times: (a) June-September, 2000, (b) March-May, 2001, and (c) March-May, 2002.

To estimate household cash income, we asked the male household head to report all the sources of income from sale and wage labor earned by all the adults in the household during the two weeks before the day of the interview. We collected data on the sale of farm and forest products disaggregated by product. We estimated household consumption of farm goods by asking the female household head to report the total amount of rice, manioc, and maize consumed in the household during the week before the day of the interview. We interviewed the main village authority to gather information on road access and walking time from the village to the nearest market town. Table 1 contains definition and summary statistics of the variables used in the regressions. Later we discuss how we dealt with possible biases from omitted variables.

How accurate and reliable are income figures obtained by restricting the recall period to a two-week period before the day of the interview, which took place during the dry season? Elsewhere (Godoy et al. n.d.[2]), we used data from a panel data set of five consecutive quarters (1999-2000) to estimate quarterly income, and found that daily quarterly monetary income during the period reached about $0.90/person/day. This daily income is within a similar range as the estimates presented here based on two-week income values. Here we found a daily income of $0.67/person/day (calculated as *Household earnings* from Table 2, averaged over three years, and divided by a household size of 4.2 adult equivalents). In our previous research, we have also found evidence of forward telescoping bias when reporting income figures, suggesting that the income figures for the last two weeks likely pick up income earned before the two-week period (Godoy et al. n.d.[1]).

Focus Groups

We used focus groups in 2001 and 2002 to gather information about the different labor and technology inputs used to cultivate rice. To capture variation in rice management, natural resource endowments, and farming skills, we carried out focus groups in half of the villages (*n*=18) taking part in the study. Villages varied in distance from the town of San Borja. We held focus groups with women and men together in the school building. We asked villagers to tell us about the number of work days needed to carry out different tasks of rice farming. We wrote answers once villagers reached a consensus. When groups disagreed, we took the mean of the responses. We also asked people to estimate yields of a standard variety of rice. For technical inputs, we asked about the time needed to fell trees with a chainsaw, to spread pesticide, and to sow rice with a manual sowing machine in a rice field of one hectare. We also asked about the cost of chemical inputs in stores in the town of San Borja.

The Model

In the first part of the next section, we estimate how cash cropping rice by Tsimane' affects deforestation after controlling for competing drivers of deforestation related to market integration (e.g., road access, distance to closest market town, cash income, and market dependence). By market dependence, we mean the share of household consumption from one's own farm plots in total household income. More formally:

Market dependence = Cash income / (cash income + consumption value of rice, maize and manioc)

We estimate the following model:

$$[1]\quad Y_{hvn+1} = a + bX_{hvn} + dT_{hvn} + fC1_{v} + gC2_{n} + h_{hvn}$$

Table 2. Rice in the Tsimane' Economy (2000-2002). Data Are Mean ± Standard Deviation.

	2000	2001	2002
Rice income[a]	13.2±32.9	9.9±21.5	6.8±14.1
Household earnings[b]	44.5±57.1	43.9±74.3	29.7±35.6
Rice % of total earnings	25.9±33.5	21.3±26.3	22.6±25.1
Percentile			
25	0	0	0
50	0	7	15
75	51	41	40
90	82	58	53
Nº Observations	511	378	331
Time survey	July-September	March-April	February-April

[a] Sum of rice transactions in cash and in kind, in US$ for past two weeks.
[b] Sum of sales in kind and cash, and wage labor, in US$ for past two weeks.

Where Y is the area deforested by household *h* in village *v*, in year *n+1*. X is the area sown with the rice of household *h* in village *v* the previous year, *n*. T is a vector of variables that reflects the strength of market participation of household *h* in village *v* of year *n*. C1 is a set of dummy variables used to control for village fixed effects, and C2 is a set of dummy variables for survey years to control for the confounding effect of survey year. To control for the effect of household size, we used the household values of area sown with rice and area cleared, each divided by the number of adult equivalents per household. The error term, h, captures the part of the variation left unexplained by the model.

To deal with possible biases from omitted variables, we included village dummies in the regression model. The procedure should allow us to control for the confounding role of village-level attributes, such as access to markets, or village endowments (e.g., soil fertility). We did not have enough degrees of freedom to run a household fixed-effect model, so the estimated parameters may be biased by unobserved household attributes that affect both rice cultivation and deforestation. For example, some households might have access to farm technologies, credit, and labor help that would affect both how much rice they cultivate and how much forest they clear. We run regressions with clustering of households by villages because households are nested in villages, and because households from a village likely show more similar deforestation patterns than households from different villages. Clustering is necessary because the units of observation, the households, are not independent of one another but clustered in natural units (villages). Clustering inflates standard errors, making them more conservative, but does not affect the coefficients we estimate.

The Simulation Model

In the second part of the results section, we explore the consequences of Tsimane' efforts to escape poverty by increasing rice production. First, we estimate the amount of forest a household would need to clear for income from rice to reach $1/person/day (poverty line). Second, we assess whether households would be able to meet the additional labor requirements of increased cash cropping and the possible role of farm technologies in easing household labor constraints. Third, we explore the consequences of increased rice production on fallow duration. We simulate five scenarios:

1. *Subsistence* scenario is a baseline scenario used for comparison. Households keep up with current area clearing to meet their needs. We adjust for a demographic increase of 4.76 percent per year, in line with current evidence about the demographic growth of the Tsimane' population (Reyes-García 2001).
2. *Poverty Line + Traditional Practice* scenario: Households choose to reach the poverty line using traditional farming practices to cultivate rice.
3. *Poverty Line + Farm Technology* scenario: Households choose to reach the poverty line with new farm technologies (i.e., herbicides and chainsaws).
4. *Poverty Line + Rice Price Increase* scenario: same as (1) but rice price increases by three percent per year.
5. *Poverty Line + Encroachment* scenario: Same as (1) but encroachment represents an increase in the number of households per village of three percent per year. We assume that encroachers follow the same deforestation pattern as do the Tsimane' households that choose to reach the poverty line.

Appendices A-B contain the assumptions, formulas, and empirical data used to simulate the five scenarios. Although most of the parameters used reflect empirical observations, some assumptions may not fully mimic the future. For instance, households split over time, some may migrate out of the area, or some may diversify their income resources by pursuing non-farm occupations. Schooling may lower the rate of demographic increase. However, we kept the assumptions simple to make the simulation easy and open to further exploration. Our estimates are conservative because we simulated the changes that would need to occur in order for households to reach the poverty threshold of $1/person/

day. However, people would probably aspire to incomes beyond this minimum value.

Results

Rice Micro-economy

During 2000, 2001, and 2002 households earned $13.2, $9.9, and $6.8 from rice in the two weeks prior to the interview, equivalent to about 26 percent, 21 percent, and 23 percent of their total cash income for the same period (Table 2). We found large variation between households in their participation in the rice market. For 50 percent of households, rice represented 0 percent, 7 percent and 14.7 percent of their income in 2000, 2001, and 2002. At the other extreme, for 10 percent of the households, rice represented 82 percent, 58 percent, and 53 percent of their total income in 2000, 2001, and 2002. Variation in rice trade, as well as the fact that households that cultivate large areas of rice also sell a lot of rice (Vadez et al. 2004), give us an ideal setting to estimate the relationship between rice cultivation and deforestation.

We first used data from focus groups to asses the various costs (in labor and money) incurred under the traditional method of cultivating rice; that is, we asses the value of traditional inputs. We found that one hectare of rice required about 101.9 person-days of work from field opening to rice harvesting (Table 3). Participants estimated an average yield of 1,540 kg/ha, which would result in a gross income of $176/ha (1 kg of rice= $0.114). We divided gross income by labor input to calculate the return on labor investment for rice: each day allocated to rice production provides an average wage of $1.72/day. This is about 66 percent of the local daily average wage for unskilled laborers for work in cattle ranches and logging concessions. Daily wages in these occupations vary by season but average about $2.60/day. Participants estimated that a typical adult could dedicate at most 170 days/year to cultivate rice because rice does not grow all year and people have other activities. Assuming that a typical household is composed of three adults (Reyes-García 2001), every household would have about 510 person-days available to cultivate rice every year.

We used information from the same focus groups to assess how modern technology would affect work inputs to cultivate rice, with particular attention to: (1) the use of chain saws to fell trees, (2) the use of manual sowing machines, and (3) the use of herbicides to replace manual weeding. The chainsaw work was estimated at two days to fell all the trees in one hectare and would cost $21.84. The cost of using manual sowing machines is $0.05/ha. Spraying herbicides would cost $9.87/ha. Total input costs for using the three technologies is $31.76/ha, which decreases the income per hectare by about 18 percent, from $176/ha with traditional practice to $144.24/ha with modern technology. However, the use of modern technology increases by 70 percent the returns to labor investment, from $1.72/day with traditional practice to $2.94/day with modern technology. The higher returns to labor investment are due to reduced work input by 52 percent, from 101.9 work person-days to 49.1 work person-days with modern technology (Table 3). In sum, the use of modern farm technologies decreases the work requirement to cultivate rice, while increasing the return on labor investment almost to the level of local unskilled wage labor.

Table 3. Summary Statistic for Labor Inputs in Rice Cultivation and other Economic Parameters. Data Are the Mean (± sd) of Data Collected in Focus Groups in 18 Villages.

Activities	Rice, traditional	Rice, modern
Field preparation		
Slashing (days/ha)	14.1±5.4	14.1±5.4
Felling (days/ha)	22.9±5.9	0
Burning-Cleaning (days/ha)	4.3±5.6	4.3±5.6
Crop management		
Sowing (days/ha)	11.7±5.1	2.3±1.0
Weeding (days/ha)	23.2±8.0	2[a]
Harvesting (days/ha)	26.4±4.5	26.4±4.5
Technology inputs		
Chainsaw[b] (US$/ha)	0	17.84
Sowing machine[c] (US$/ha)	0	0.05
Herbicide[d] (US$/ha)	0	9.87
Economic parameters		
Yield (kg/ha)	1540±241	1540±241
Total work (days/ha)	101.9	49.1
Total input (US$/ha)	0	31.76
Net income (US$/ha)	176	144.24
Productivity of work (US$/day)	1.72	2.94

[a] Data estimated from information with Tsimane' key informants
[b] Two days wage (7.89 US$/ha), 10 liters of gas (3.95 US$/ha), cost and maintenance (10 US$/ha)
[c] Cost 5.26 US$ and would work for about a 100 ha minimum, that is 0.05 US$/ha
[d] Chemical inputs: 6.58 US$/ha, plus 3.29 US$ per ha for rental, based on the pump price

Regressions

Rice Cash Cropping

We used expression [1] to estimate the relation between the area of rice sown in a given year and the total area cleared the following year. Using untransformed data, we found that the area of rice sown in year *n* bore a highly significant positive relation to the total area deforested in year *n+1*. An additional hectare of rice planted was associated with 0.30 more hectares deforested in the subsequent year (Table 4). Results were similar whether using village or

Table 4. Regression with Total Deforestation, First with Raw Data (Column 1 & 2), and with the Logarithm of Deforestation and Rice Rrea (Column 3 & 4). Data Are the Regression Coefficients with Standard Errors in Brackets. Significance at the 99, 95 and 90% Level Indicated with *, **, and *.**

Deforestation	Raw data		Logarithm	
Rice area	0.300***	0.306***	-	-
	(0.096)	(0.097)		
Log (rice area)	-	-	0.263***	0.276***
			(0.044)	(0.040)
Walking time	NA	-0.0017	NA	-0.0056
		(0.0013)		(0.0045)
Road access	NA	0.0023	NA	0.0272
		(0.0299)		(0.0824)
Cash income	0.211	0.345	0.812	1.166**
	(0.186)	(0.157)	(0.443)	(0.389)
Market dependence	0.054	0.041	0.087	0.104
	(0.078)	(0.057)	(0.168)	(0.132)
Observations	463	463	449	449
R^2	0.14	0.07	0.21	0.12
Village dummy variables	Yes	No	Yes	No

NA, non applicable. Variables taken out of regressions using village dummies.

year dummies. We re-estimated expression [1] taking the logarithm of total area deforested and area planted with rice to obtain elasticity coefficients (i.e., the percentage change in the dependent variable from a one percent change in the explanatory variable). We found that the area planted with rice bore a significant positive association with the area deforested. A two-fold increase in the area cultivated with rice correlated with about a 26-27 percent increase in the total area deforested by a household during the following cropping season (Table 4). Results were similar when using village and year dummies.

To assess whether rice cultivation is also associated with greater deforestation of old-growth forest, we re-estimated expression [1] using the amount of old-growth forest cleared (instead of total area cleared) as a dependent variable. For this estimation, we used a Tobit regression because 48 percent of households did not clear old-growth forest. The area sown with rice in year *n* was associated with a significant increase in the clearing of old-growth forest the following year (Table 5). An additional hectare cultivated with rice was associated with an increase of 0.17 and 0.18 hectares of old-growth forest cleared. The lower estimate corresponds to a regression that controls for village fixed effects and survey year, while the higher estimate comes from a regression without such controls.

We took the logarithm of old-growth forest and rice area and ran the same regressions to obtain elasticity coefficients. The area sown with rice (in logarithms) showed a highly significant relationship to deforestation of old-growth forest in the next cropping season. Doubling the area of rice was associated with a 26 percent increase in old-growth forest clearing in the regression using dummy variables to control for village fixed effects and survey year. In the regression with no such controls, doubling the area sown with rice was associated with a 28 percent increase in old-growth deforestation (Table 5). Since many households did not clear old-growth forest, we added +1 to the dependent variable. The regressions retained their significance, but elasticity coefficients were much lower than in the Tobit regressions; the elasticity was 0.032 ($p<0.002$) in the regression using dummy variables to control for village fixed effects, and 0.030 ($p<0.02$) in the regression using no such controls.

In sum, the area cultivated with rice in year *n* is positively associated with the amount of area cleared by the household in year $n+1$, even after controlling for village fixed effects and survey year. Results suggest that the observed association between cash cropping and deforestation does not reflect village attributes or time variant aspects. Rather, deforestation probably has more to do with household characteristics.

Other Variables of Market Integration

We estimated the correlation between deforestation and two village-level variables: walking time to the nearest market town and permanent road access for vehicles. Walking time to the nearest market town bore no significant statistical associations with deforestation, either when using total area cleared ($p<0.31$) or when using the logarithm of old-growth forest cleared ($p<0.12$; Table 5). Permanent road access for vehicles had no significant statistical association

Table 5. Regression with Old-growth Forest Deforestation, First with Raw Deforestation Data (Columns 1 & 2), and with the Logarithm of Old-growth Forest and Rice Area (Columns 3 & 4). Data Are the Regression Coefficients with Standard Errors in Brackets. Significance at the 99, 95 and 90% Level Indicated with *, **, and *.**

Old-growth forest	Tobit regression		Log of old-growth forest	
Rice area	0.175**	0.178**	-	-
	(0.076)	(0.077)		
Log (rice area)	-	-	0.256***	0.278***
			(0.076)	(0.074)
Walking time	NA	0.0026	NA	-0.0096
		(0.0016)		(0.0059)
Road access	NA	-0.0056	NA	-0.0025
		(0.0334)		(0.0986)
Cash income	0.225	0.654***	0.295	0.053
	(0.272)	(0.253)	(0.507)	(0.517)
Market dependence	0.071	0.057	0.397	0.564**
	(0.063)	(0.055)	(0.336)	(0.235)
Observations	463	463	259	259
R^2	0.29	0.05	0.32	0.15
Dummy variables	Yes	No	Yes	No

NA, non applicable. Variables taken out of regressions using village dummies.

with total or with old-growth deforestation in any of the regressions.

We also looked at two other household-level proxies for integration to the market: household cash income and household market dependence. In the regression with raw data for total deforestation as a dependent variable, there was no significant statistical association between cash income in year *n* and total forest area cleared in year *n+1* (columns 1 and 2, Table 4). In the regression using logarithmic data and no dummy variables to control for village fixed effects and year effects, there was a significant statistical association between cash income and total deforestation (column 4, Table 4). In the Tobit regression with the clearing of old-growth forest without controls for village fixed effects and year effects (column 2, Table 5), we found a statistically significant relation between cash income and old-growth forest clearing. In the regressions using logarithmic data of old-growth forest, we did not find a significant association between cash income and old-growth forest clearing (columns 3 and 4, Table 5).

Households' market dependence in year *n* bore no significant association with total deforestation in year *n+1* (Table 4). The explanatory variable had only a weak statistical association with the level of deforestation of old-growth forest in the regression using the logarithm of old-growth forest and without dummy variables for year and village fixed effects ($p<0.05$). Doubling the degree of market dependence was associated with 56 percent more deforestation of old-growth forest (column 4, Table 5).

In sum, among the various explanatory variables for deforestation, cultivation of rice in year *n* bore the largest association with area cleared in the year *n+1*. The finding supports the intuition that there may be strong incentives for rice production in the study area.

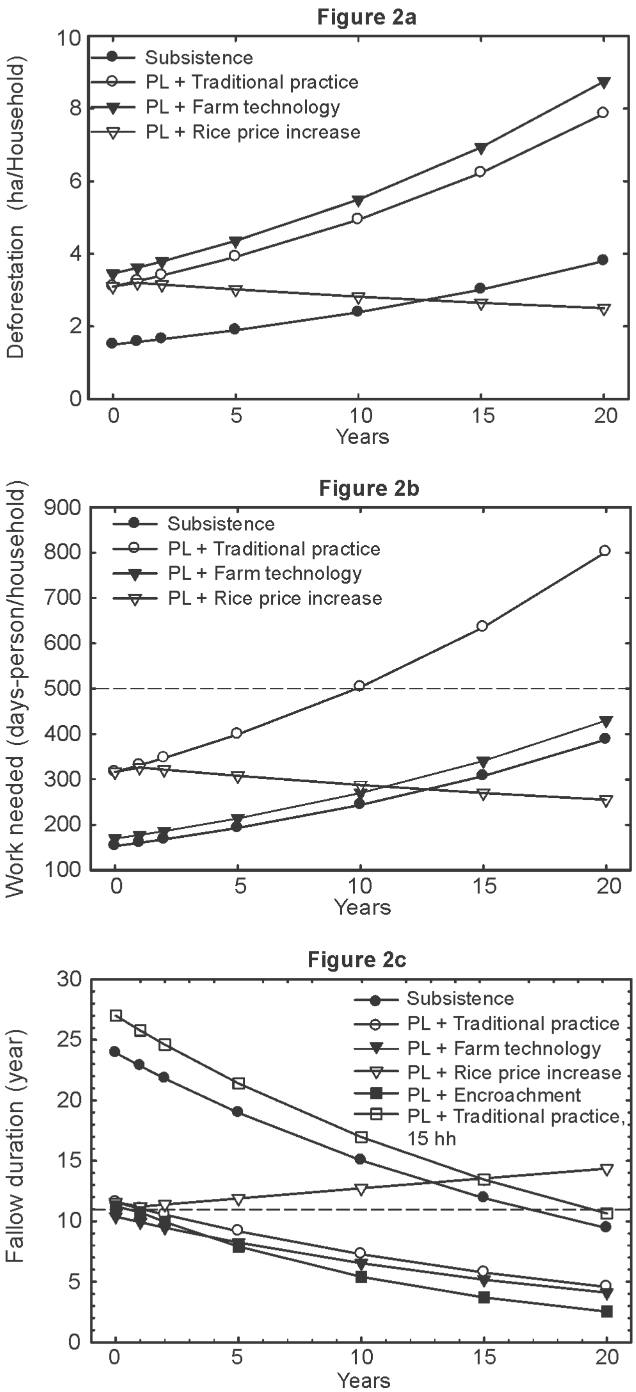
Can Poor Rural Households Cash Crop Themselves Out of Poverty?

We have seen that Tsimane' households obtained on average about 21-26 percent of their cash earnings through the sale of rice and that 25 percent of all the households obtained up to 40-50 percent of their cash income through rice. Since rice is in high demand in the local market, but local supply does not meet local demand, and since Tsimane' income per capita is only about $0.90/person/day (Godoy et al. 2002), below the $1/person/day poverty line defined by the World Bank, it is reasonable to assume that Tsimane' would rely on the sale of rice to increase income. Based on those assumptions, we simulate what would happen to land and labor requirements and to fallow duration if Tsimane' decide to cash crop rice to reach the poverty line.

Enough Land to Go beyond the Poverty Line?

Keeping up with current needs and simply adjusting for demographic increase, a typical Tsimane' household in the

Figure 2. Consequences of Reaching the Poverty Line with a 4.76% Demography Increase on: Forest Clearance Per Household (Fig. 2a), Work Required to Cultivate (Fig. 2b), Fallow Duration in Situations of Varying Land Availability (Fig. 2c).



subsistence scenario would need to clear 2.4 ha of forest within 10 years and about 3.8 ha within 20 years. This represents a 60 percent and 160 percent increase in the current level of deforestation (Fig. 2a). Under the *Poverty Line + Traditional Practice* scenario, a typical Tsimane' household would need to clear 4.9 ha within 10 years, or over three times more than they currently cut. Within 20 years, Tsimane' households would need to clear 7.9 ha of forest, over five times more than they currently cut (Figure 2a). Forest clearance under the *Poverty Line + Farm Technology* scenario resembles the *Poverty Line + Traditional Practice* scenario.

The simulation suggests that simply adjusting to demographic increase with current needs would require large increases in the amount of forest area cleared for rice. For that reason, we explore a scenario where an increase in the price of rice would raise the gross income per hectare. Under the *Poverty Line + Rice Price Increase* scenario, forest clearance would be 3.1 ha in year 0, about twice as high as the current level of forest cleared by households. It would then decrease to 2.8 ha within 10 years, about equal to the current *subsistence* scenario, and then decrease to 2.5 ha within 20 years, lower than clearance in the *subsistence* scenario, but still 66 percent higher than clearance at time 0 in the *subsistence* scenario.

Enough Work to Meet the Poverty Line?

Since reaching the poverty line would require a large increase in the area sown with rice, the possibility of Tsimane' households meeting the poverty threshold through rice cultivation may become primarily a matter of work availability. We found that in the *subsistence* scenario, households would have sufficient labor availability for the next 20 years, when they would need 387 person-days/household to meet labor requirements. In the *Poverty Line + Traditional Practice* scenario, a typical household would need 316 days to reach the poverty line in year 0, i.e. 163 more days than under the *subsistence* scenario. A household would need 503 days within 10 years to reach the poverty line (Figure 2b). After 10 years, households choosing to reach the poverty line with no technology input would not be able to meet the labor requirements. In contrast, under the *Poverty Line + Farm Technology* scenario, the labor requirements would be very close to the labor requirements of the subsistence scenario. Households would need 169 person-days of work in year 0, only 16 more days than under the *subsistence* scenario, and 269 persons-days within 10 years, only 26 more days than under the *subsistence* scenario, but 230 days less than in the *Poverty Line + Traditional Practice* scenario. Even after 20 years, the *Poverty Line + Farm Technology* scenario would remain largely below the 510 person-day ceiling of yearly available labor per household.

Although the use of simple farm technologies may help households meet the labor requirements of reaching $1/person/day, the work demand would increase over time and would end up imposing a binding constraint on households. In the *Poverty Line + Rice Price Increase* scenario, the labor requirement would decrease over time because the amount of forest clearance needed to reach the poverty line would also decrease (Figure 2a). Under that scenario, in years 0, 10, and

20 a household would need 316, 287, and 254 days-person of labor each year to reach the poverty line.

Fallow Duration to Reach the Poverty Line

If poor households want to reach the poverty line by selling rice, the fallow duration will be linked to the number of households in the village. We assume a typical village size of 35 households and a fallow period of at least 11 years to allow secondary forest re-growth and to avoid land degradation (Metzger 2002). We compare the fallow duration under different scenarios to this benchmark using the same simulations as in the previous sections. Then, we add a simulation for the *Poverty Line + Traditional Practice* scenario in a small village of 15 households. We also consider the case of encroachment by colonists, equivalent to a 3 percent/year increase in the number of households in the village (Appendix B).

With current land availability and a household clearance of 1.5 ha/year, the fallow duration is about 24 years in a village of 35 households. Under the *subsistence* scenario, the fallow duration would decrease to about 9.5 years within 20 years in a village of 35 households. Under the *Poverty Line + Traditional Practice* scenario, the fallow duration would decrease to 11.6 years in year 0, about a two-fold reduction compared with the *subsistence* scenario, and to 7.3 years within 10 years, below the minimum fallow period of 11 years. Under the *Poverty Line + Farm Technology* scenario, the fallow duration would decrease to 10.4 years in year 0 and to 6.5 years within 10 years, below the 11 years fallow period, and about the same as the *Poverty Line + Traditional Practice* scenario. In contrast, under the *Poverty Line + Traditional Practice* scenario in a small village of 15 households, the fallow duration would be 27.0 years in year 0; it would then decrease to 17.0 years within 10 years, and to 10.6 years within 20 years.

Under the *Poverty Line + Rice Price Increase*, the fallow duration in a village of 35 households would be about 11.6 years in year 0, it would increase to 12.7 years within 10 years, and to 14.3 years within 20 years. Under the *Poverty Line + Encroachment* scenario, the fallow duration would dramatically decrease over time and would reach only 5.4 years within 10 years and about 2.5 years within 20 years.

Discussion and Conclusions

Cash cropping rice in a given year was positively associated with the total area cleared by a household the following cropping season. Every additional hectare cultivated with rice in year *n* was associated with 0.26-0.30 more hectares deforested in year *n+1* and with 0.17-0.28 more hectares of old-growth forest cleared in year *n+1*. Though the increase is modest, the statistically significant and positive association between cash cropping and clearing of old-growth forest, which is available chiefly in distant villages, suggests that cash cropping rice is expanding to remote areas. The high demand for rice in the local market, and the importance of rice in the household economy, suggests that rice cultivation is likely to fuel more deforestation in coming years. We found no statistically significant association between deforestation and permanent road access to the villages. We found a weak statistical association between deforestation and walking time to the nearest market, which could be explained because despite permanent road access by vehicle, many villages cannot rely on a regular transportation service on these roads.

Our simulations suggest that if people try to escape poverty by intensifying cash cropping of rice, the labor demands on the household will grow. Reaching the poverty line of $1/person/day by cash cropping rice would require doubling the area of forest cleared per household. If one adds demographic increase, the level of deforestation would triple in a decade. Two possible options to alleviate Tsimane' pressure on the land would be an increase in the price of rice, or the substitution of rice with another, more profitable cash crop.

Reaching the poverty line would also stimulate important changes in households' time allocation because expanding rice crops would require additional work. We estimate that within 10 years, households facing population growth without access to new farm technologies would find it hard to meet the work requirements needed to reach the poverty line. Technological improvements that save labor could ease labor constraints, but only temporarily. Even under such a scenario, the demographic increase would soon overshadow the benefits of technological improvements.

Reaching the poverty line by cash cropping rice would also reduce the duration of the fallow period, in agreement with previous work (Coomes, Grimard, and Burt 2000). Reduction of the fallow period will be more acute in large villages facing land scarcity and more so if encroachment by outsiders occurs. Land constraints would eventually also affect households in small villages. Land-saving technological improvements might ease these constraints.

Although rice cash cropping is currently having only modest impacts on the amount of forest area cleared, the socioeconomic context in which poor rural households live—the desire to increase income, the high demand for farm products, and the demographic increase—suggests that cash cropping rice, and associated deforestation, may increase. In light of the low returns to labor input, and the high demand for land to cultivate rice, the reconciliation of forest conservation and economic development requires new alternatives. We conclude with three recommendations to help reconciliate forest conservation and economic development related to cash cropping by small holders.

First, a rise in the price of rice would increase profitability per hectare of land and decrease the amount of forest required to reach the poverty line. An increase in the price of rice would also have direct effects on labor requirements and fallow duration. It would benefit the economy of smallholders, but would lower the real income of poor urban households that buy rice. An alternative option is to find a more profitable cash crop to substitute for rice. Research is needed to explore potential high profitability market crops.

Second, the large labor demand required by rice cultivation would boost the use of locally available farm technologies to reduce labor, namely chainsaws and herbicides. The use of chemicals in farming has risks for users and for the environment, but could reduce labor requirements. Extension work is needed to help farmers use those technologies in appropriate ways.

Third, herbicides and chain saws are labor-saving technologies but they do not increase the productivity of rice. Agricultural research and extension in the area are needed to increase rice productivity. A promising area of research is to find a sustainable way to intensify production of cash crops on the same land. As nitrogen is the most limiting edaphic factor for crop production (Sinclair and Vadez 2002), the use of nitrogen-fixing legumes might provide a sustainable way of increasing agricultural production. Work is needed to find and introduce such legumes, as they need to be marketable and adopted by the population.

References

Alston, Lee, Gary D. Libecap, and Bernardo Mueller
2000 Land Reform Policies, the Sources of Violent Conflict, and Implications for Deforestation in the Brazilian Amazon. Journal of Environmental Economic Management 39(2):162-188.

Angelsen, Arild, and David Kaimowitz
1999 Rethinking the Causes of Deforestation: Lessons from Economic Models. World Bank Research Observer 14(1):73-98.
2001 Agricultural Technologies and Tropical Deforestation. Oxford, United Kingdom: Center for International Forestry Research.

Byron, Elizabeth
2003 Market Integration and Health: The Impact of Markets on the Nutritional Status, Morbidity, and Diet of the Tsimane' Amerindians of Lowland Bolivia. Gainesville: University of Florida Press.

Chicchon, Avecita
1992 Chimane Resource Use and Market Involvement in the Beni Biosphere Reserve, Bolivia. Gainesville: University of Florida Press.

Chomitz, Kenneth M., and David A. Gray
1996 Roads, Land Use, and Deforestation: A Spatial Model Applied to Belize. World Bank Economic Review 10(3):487-512.

Comisión Europea
2000 Mercados agroalimentarios en Bolivia: El caso de arroz, maíz, trigo, y papa. Apuntes técnicos n 4. La Paz: Unidad de Seguridad Alimentaria. URL:<http://europa.eu.int/comm/europeaid/projects/resal/Download/report/mission/bolper/1200tnbol.pdf> 15th April 2004).

Coomes, Oliver T., Franke Grimard, and Graeme J. Burt
2000 Tropical Forests and Shifting Cultivation: Secondary Forest Fallow Dynamics Among Traditional Farmers of the Peruvian Amazon. Ecological Economics 32:109-124.

Costanza, Robert, Ralf D'Arge, Rudolf de Groot, Steven Farber, Monica Grasso, Bruce Hannon, Karin Limburg, Shahid Naeem, Robert V. O'Neill, Jose Paruelo, Robert G. Raskin, Paul Sutton, and Marjan Van den Belk
1997 The Value of the World's Ecosystem Services and Natural Capital. Nature 387:253-260.

Daillant, Isabelle Sens Dessus Dessous
2003 Organization sociale et spatiale des Chimane d'Amazonie boliviane. Nanterre, France: Societe d'ethnologie.

Deacon, Robert T.
1999 Deforestation and Ownership: Evidence from Historical Accounts and Contemporary Data. Land Economics 75(3):341-359.

Dearden, Philip
1995 Development, the Environment and Social Differentiation in Northern Thailand. *In* Counting the Costs: Environmental Growth and Economic Change. Jonathan. Rigg, ed. Pp. 111-130. Pasir Panjang, Singapore: Institute of Southeast Asian Studies (ISEAS).

Ellis, Rebecca
1996 A Taste for Movement: An Exploration of the Social Ethics of the Tsimane' of Lowland Bolivia. Scotland: St Andrews University.

Finegan, Brian
1996 Pattern and Process in Neotropical Secondary Rain Forest: The First 100 Years of Succession. Trends in Ecological Evolution 11(3):119-124.

Godoy, Ricardo
2001 Indians, Markets, and Rainforest: Theory, Methods, and Analysis. New York: Columbia University Press.

Godoy, Ricardo, Kris N. Kirby, and David Wilkie
2001 Tenure Security, Private Time Preference, and Use of Natural Resources among Lowland Bolivian Amerindians. Ecological Economics 38(1):105-118.

Godoy, Ricardo, William R. Leonard, Thomas. W. McDade, Victoria Reyes-García, Susan Tanner, and Tomas Huanca
n.d.[1] Can We Trust an Adult's Estimate of Parental School Attainment? Field Methods. In press.

Godoy, Ricardo, Han Overman, Josefin. Demmer, Lilian Apaza, Elizabeth Byron, Tomas Huanca, William R Leonard, Eddy Perez, Victoria Reyes-García, Vincent Vadez, David Wilkie, Adony Cubas, Kendra McSweeny, and Nicolas Brokaw
2002 Local Financial Benefits of Rain Forests: Comparative Evidence from Amerindian Societies in Bolivia and Honduras. Ecological Economics 40(3):397-409.

Godoy, Ricardo, Victoria Reyes-García, William R. Leonard, Tomas Huanca, Thomas W. McDade, Susan Tanner, and C. Seyfried
n.d.[2] On the Measure of Income in Autarky and the Economic Unimportance of Social Capital. Journal of Anthropological Research. In press.

Hecht, Susan, and Alexander Cockburn
1989 The Fate of the Forest: Developers, Destroyers, and Defenders of the Amazon. New York: Harper Perennia.

Holden, Stein
1993 Peasant Household Modeling: Farming Systems Evolution and Sustainability in Northern Zambia. Agricultural Economics 9(3):241-267.

Huanca, Tomas
1999 Tsimane' Indigenous Knowledge: Swidden Fallow Management and Conservation. Gainesville: University of Florida Press.

2007 Tsimane' Oral Tradition, Landscape, and Identity in Tropical Forest. La Paz, Bolivia: Campo Iris. 2007.

Humphries, Sally
1993 The Intensification of Traditional Agriculture among Yucatec Maya Farmers: Facing Up to the Dilemma of Livelihood Sustainability. Human Ecology 21(1):87-103.

Jones, Donald, Virginia Dale, John Beaucamp, Marcos A Pedlowsky, and Robert O'Neill
1995 Farming in Rondonia. Resource and Energy Economics 17(2):155-188.

Kaimowitz, David, and Arild Angelsen
1998 Economic Models of Tropical Deforestation, A Review. Bogor, West Java: Center for International Forestry Research.

Marquette, Catherine M.
1998 Land Use Patterns Among Small Farmer Settlers in the Northeastern Ecuadorian Amazon. Human Ecology 26(4):573-598.

McMorrow, Julia, and Abdul M. Talip
2001 Decline of Forest Area in Sabah, Malaysia: Relationship to State Policies, Land Code and Land Capability. Global Environmental Change 11:217-230.

Mertens, Benoit, William D. Sunderlin, Ousseynou Ndoye, and Eric F. Lambin
2000 Impact of Macroeconomic Change on Deforestation in South Cameroon: Integration of Household Survey and Remotely-sensed Data. World Development 28(6):983-999.

Metzger, Jean-Paul.
2002 Landscape Dynamics and Equilibrium in Areas of Slash-and-Burn Agriculture with Short and Long Fallow Period (Bragantina Region, NE Brazilian Amazon). Landscape Ecology 17(5):419-431.

Palm, Cheryl. A., Steven A. Vosti, Pedro A. Sanchez, and Polly J. Ericksen
2005 Slash-and-Burn Agriculture: The Search for Alternatives. New York: Columbia University Press.

Pendleton, Linwood H., and Lance E. Howe
2004 Market Integration, Development, and Smallholder Forest Clearance. Land Economics 78(1):1-19.

Pérez-Diez, Andres
1983 Etnografía de los Chimane del Oriente Boliviano. Buenos Aires, Argentina: Universidad de Buenos Aires.

Perz, Steven G.
2004 Are Agricultural Production and Forest Conservation Compatible? Agricultural Diversity, Agricultural Incomes, and Primary Forest Cover Among Small Farm Colonists in the Amazon. World Development 32(6):957-977.

Picchi, Debra
1991 The Impact of an Industrial Agricultural Project on the Bakairi Indians of Central Brazil. Human Organization 50(1):26-38.

Pichón, Francisco, Catherine Marquette, Laura Murphy, and Richard Bilsborrow
2002 Endogenous Patterns and Processes of Settler Land Use and Forest Change in the Ecuadorian Amazon. *In* Deforestation and Land Use in the Amazon. Charles Wood and Roberto Porro, eds. Pp. 241-280. Gainesville: University of Florida Press.

Piland, Richard
1991 Traditional Chimane Agriculture and Its Relationship to Soils of the Beni Biosphere Reserve, Bolivia. Gainesville: University of Florida Press.

Reid, John.
2001 Roads and Tropical Forests: From White Lines to White Elephants. *In* Footprints in the Jungle: Natural Resource Industries, Infrastructure, and Biodiversity Conservation. Ian A. Bowles and Glen T. Prickett, eds. Pp. 281-291. New York: Oxford University Press.

Reyes-García, Victoria
2001 Indigenous People, Ethnobotanical Knowledge, and Market Economy: A Study of the Tsimane' Amerindians, Bolivia. Gainesville: University of Florida Press.

Rudel, Thomas K.
2005 Tropical Forest: Regional Paths of Destruction and Regeneration in the Late 20th Century. New York: Columbia University Press.

Silver, Whendee, Sandra Brown, and Ariel Lugo
1996 Effects of Changes in Biodiversity on Ecosystem Function in Tropical Forest. Conservation Biology 10(1):17-24.

Sinclair, Thomas. R., and Vincent Vadez
2002 Physiological Traits for Crop Yield Improvement in Low N and P Environment. Plant Soil 245(1):1-15.

Smith, Joyotee., Petra. van de Kop, Kenneth Reategui, Ignacio Lombardi, Cesar. Sabogal, and Armando. Diaz
1999 Dynamics of Secondary Forests in Slash-and-Burn Farming: Interactions Among Land Use Types in the Peruvian Amazon. Agriculture, Ecosystems, and Environment 76(2-3):85-98.

Tungittiplakorn, Warapong, and Philip Dearden
2002 Biodiversity Conservation and Cash Crop Development in Northern Thailand. Biodiversity and Conservation 11:2007-2025.

Vadez, Vincent, Victoria Reyes-García, Lilian Apaza, Elizabeth Byron, Tomas Huanca, William R Leonard, Eddy Perez, and David Wilkie
2004 Does Integration to the Market Threaten Agricultural Diversity? Panel and Cross-sectional Evidence from a Horticultural-foraging Society in the Bolivian Amazon. Human Ecology 32(5):635-646.

Vadez, Vincent, Victoria Reyes-García, Ricardo Godoy, William R Leonard, Lilian Apaza, Elizabeth Byron, Tomas Huanca, William Leonard, Eddy Perez, and David Wilkie
2003 Validity of Self-reports to Measure Deforestation: Evidence from the Bolivian Lowlands. Field Methods 15(3):289-304.

Appendix A. Basic Calculations and Assumptions of Simulations

Area cleared under the different scenarios. The additional forest clearance needed in year 0 to reach the \$1/person/day (\$365/person/year) poverty threshold was

[2] $FC_0 = CCR + [(PL-I)*HHC/(RGM*CRPL)]/PRO.$

Where FC_0 is the forest cleared in year 0; CCR is the current clearing amount, 1.5ha/hh/year (Vadez et al. 2004); PL is the poverty line (\$365/person/year); I is the average Tsimane' income per person (cash + consumption), estimated to \$332/person/year (Godoy et al. 2002); HHC is the household composition, 6.5 persons/household (this study); PRO is the share of newly opened fields planted with rice, 76 percent (this study); RGM is the rice gross income, \$176/ha with no modern technology input (this study); CRPL is the contribution of rice to meet poverty line, assumed to be 100 percent.

Then, FC_n the additional forest clearance needed in year n was such as:

$FC_n = FC_0*(1 + DI/100)^n$

[3] $FC_n = [1.5 + [(33)*6.5/RGM]/0.76]* (1 + 4.76/100)^n$

Where DI is the demographic increase, estimated to 4.76 percent (Reyes-García 2001).

Work needed under different scenarios. From expression [3], we calculated the work required to reach poverty line in year n, such as:

$Work = RLR*FC_n$

[4] $Work = RLR*[1.5 + [(33)*6.5/RGM]/0.76]*(1 + 4.76/100)^n$

Where: RLR, the rice labor requirement varies from 102 days-person/ha (*Poverty Line + Traditional farming*) to 49.1 days-person/ha (*Poverty Line + Farm technology*).

Fallow duration under the different scenarios. From expression [3], we calculated the fallow duration to reach poverty line in year n, such as:

$Fallow\ duration = LA/(VS*FC_n)$

[5] $Fallow\ duration = LA/(VS*[1.5 + [(33)*6.5/RGM]/0.76]*(1 + DI/100)^n$

Where LA, the land availability per village and is estimated to 1250ha, and VS, the village size varies between 15 households (small villages) and 35 households (large villages).

Appendix B. Summary of the Main Assumptions Made in the Different Scenarios Concerning the Area to Be Cleared Per Household, the Fallow Duration, and the Labor Requirement, to Meet Poverty Line with a 4.76 Percent Demographic Increase. Main Varying Parameter is Indicated in Bold.

Scenarios	Main assumptions: Area to be cleared and Work	Main assumptions: Fallow
Subsistence	$Fn = 1.5*(1+DI/100)^n$ with DI = 4.76%/y	VS = 35 hh
PL + Tradional Practice	RGM = 176 US\$/ha; DI = 4.76%/y	VS = 35 hh
PL + Farm technology	RGM = 144 US\$/ha; DI = 4.76%/y	VS = 35 hh
PL + Rice price increase	RGM = \$176/ha; DI = 4.76%/y; Price increase = 3%/y	VS = 35 hh
PL + Tradional Practice	-	RGM = \$176/ha; DI = 4.76%/y; VS = 15 hh
PL + Encroachment	-	VS increase = 3%/year due to encroachment: $VS_n = 15*(1+3/100)^n$