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Impacts of soil quality differences on deforestation, use of cleared land, and farm income

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ABSTRACT. Preparing regional development strategies for the Amazon Basin is a vexing task for policymakers. Forests continue to fall and agriculture to move in to a region with patchy (in terms of agronomic potential) yet broadly nutrient-poor soils. The spatial distribution of soil types is not well mapped at finer scales relevant for agriculture. There is, moreover, little evidence about how farm land use or farm household welfare varies by soil quality in this frontier setting. Despite these information gaps, regional planners continue to use soils as a basis for policy action, some of which may influence future options for the Amazon. This paper uses a farm-level bioeconomic model that captures soil-quality-specific degrading effects of agricultural activities to assess the impacts of soil quality differences on deforestation, use of cleared land, and smallholder income in the

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western Brazilian Amazon. Focusing on an archetypical area farm with reasonable market access but limited access to labor and credit, simulations show soil quality mattered more for income than for deforestation or land use, although extremely cash-strapped farmers on poor-quality soils could face displacement. Pasture dominated farm land use across all soil types as farm forest disappeared within a generation on successfully established farms. Good- and (viable) poor-soil farms had slightly slower deforestation rates than their medium-soil counterparts – rich-soil farms shifting small amounts of area (and labor) to the more nutrient- and labor-intensive annuals, and (even viable) poor-soil farms lacking sufficient resources to clear and farm additional land. Farms with good soils could generate about 44 per cent more income than their viable poor-soil counterparts, but the lower-income level still surpassed thresholds for meeting food security and other needs. At no combination of income level and soil quality explored did the (simulated) farmer find it worthwhile to purchase and apply chemical fertilizer; nutrients came instead from secondary forest fallow, whose area rose or fell in step with annual cropping area. The implications of these results for land-use zoning, forest conservation, poverty alleviation, and other policies are discussed.

Introduction

The disappearance of tropical moist forests in developing countries and the accompanying losses of biodiversity, carbon, and other environmental services are large and growing concerns (Tomich *et al.*, 2004; Andersen *et al.*, 2002). Even more pressing in many countries is the need to modify current uses of forested areas to help meet poverty alleviation objectives (Scherr *et al.*, 2003; Lele *et al.*, 2000; World Bank, 2000). Virtually every country still with such forest is developing and applying policies such as land-use planning – often with substantial input from the international community (e.g., Chomitz and Thomas, 2003; Davis *et al.*, 1997; Fischer *et al.*, 1998) – to control how much and where forests are felled (Government of the State of Acre, 2000; de Camino, 1999). The goal is to improve human welfare within and outside forested areas.

This is the case for the Amazon, where soils are known to vary significantly (Cerri *et al.*, 2004) but precise geographical boundaries between soil types are still not well delineated (Embrapa, 1981). Some have contended that soils in the Brazilian Amazon cannot on average support sustained agricultural production at levels sufficient to meet the basic needs of small-scale agriculturalists (Fearnside, 1983; Hecht, 1993). This could set up a dynamic in which farmers abandon degraded land and move ever further into forests, slashing and burning in order to get nutrients for crops. Indeed, state-level zoning exercises often set aside the region's poorest-quality soils as reserve areas on the assumption of their limited potential to contribute to regional development and potential for worsening poverty (even as deforestation continued) if smallholders settled there (e.g., Government of the State of Acre, 2000).

Yet despite considerable knowledge about Amazonian soils' properties prior to and after conversion to agriculture (Sanchez, 1976; Sanchez *et al.*, 1982; Government of Brazil, 1979; Faminow, 1998: ch. 2; Moraes *et al.*, 1996) and broad agreement that most Amazonian soils cannot sustain continued annual crop production without fertilizer or long fallows (Serrão and Homma, 1993), less is understood about the capacity of these soils to sustain human welfare looking beyond annual cropping to all viable land-use combinations and sequences (Vosti *et al.*, 2001b). Still less is known about how soil quality – via such land-use sequences and farmer welfare – influences how much forest falls and how quickly. Throughout much of the southern Brazilian Amazon, the conversion process involves dominance of pasture systems (Andersen *et al.*, 2002; Valentim and Andrade, 2004; Valentim, 2002; Mertens *et al.*, 2002) on farms of all sizes amid improvement in general (aggregate) human welfare indicators, and mounting evidence that Amazonian farmers do turn a profit (Andersen *et al.*, 2002; Faminow, 1998; Vosti *et al.*, 2002; Valentim and Vosti, 2005).

While soils are known to play a pivotal role in meeting an array of food security, environmental, and other objectives (Lal, 2001), the role of soil quality in tropical deforestation remains obscure. In a broad review of economic models of tropical deforestation, Kaimowitz and Angelsen (1998) conclude the evidence on soil quality's effects is to date mixed. Deininger and Minten (2002), Pfaff (1999), Southgate *et al.* (1991) and Pichón (1997) all find better soil quality increases deforestation (working, respectively, in Mexico, the Brazilian Amazon, and the last two in the Ecuadorian Amazon). Other studies, including Laurance *et al.* (2002) and Jones *et al.* (1995) in the Brazilian Amazon, and Nelson and Hellerstein (1997) for Mexico, find no link between soil fertility and deforestation.[1] Still other studies, among them Andersen *et al.* (2002) (in the Brazilian Amazon) and Tachibana *et al.* (2001) (in Vietnam), indicate that better soil quality slows deforestation, or that thresholds of soil quality may matter for the link (with only the worst soil quality associated with increased pressure on forests) (Vosti *et al.*, 2002, for the study region discussed here).

Mixed results on soil fertility and deforestation could be due to many sources – measurement error (especially an issue for soil maps), mismatch of study units of observation and levels of farmer decision making, or improper time frames to capture hypothesized effects (Deininger and Minten, 2002). This could lead to the absence from the sample of those who felt the effects of soil degradation most strongly (Deininger and Minten, 2002), or mean that observed outcomes already encompass farmer adaptations, making soil quality effects on deforestation more difficult to detect (Jones *et al.*, 1995). Theory suggests that farmers would take soil quality into account – alongside other available resources and opportunities – when making product choice and technology decisions (Ochoa-Gaona and Gonzalez-Espinosa, 2000; Vosti *et al.*, 2002). Farmers would be expected to innovate ways of maintaining a livelihood from poor soils – looking to products beyond annuals – if this were possible.

More formally, rational farmers working within perfect product and factor markets will convert land from forest to alternative uses, as long as to do so adds to farm profits. If improved soil quality lowers production costs per output unit, then – in a perfect market setting – the farmer can increase profits by converting more forest to the same productive activity

[1] Although the Mexico study did find that lower agronomic potential due to other biophysical factors – notably slope and elevation – did increase the likelihood of land remaining forested.

using the same technology as long as relevant markets can absorb additional production without serious price shifts. Other things being equal, higher soil quality in a given locale should make forest clearing more likely (Deininger and Minten, 2002), since it would contribute relatively more to productivity under agriculture than under a (nutrient cycling) forest system (Pfaff,1999).

In a more realistic developing country setting of imperfectly functioning markets, farmers' limited access to funds and manpower can dictate which technologies farmers can adopt (perhaps leaving more profitable ones by the wayside) or how much area they can cultivate. Better soil quality should mean higher farmer welfare, but could also allow a shift in technology and product mix, resulting in either more or less land in cultivation (and deforestation). The outcome depends not only on relative profitability, but also the absolute and relative requirements of the various technologies for farmers' (scarce) capital and labor inputs (Angelsen and Kaimowitz, 2001; Lee *et al.*, 2001). It also hinges on household consumption decisions, especially about leisure (Singh *et al.*, 1986).

Soil quality and other constraints on farmer decision making change over time in response to cropping and management decisions. Soil is a renewable resource; the farmer chooses the rate at which its fertility is depleted or regenerated. A rational farmer would balance the gains to be garnered from drawing down soil fertility against the cost of replenishing it over the long term. A property rights regime can critically affect this calculation: farmers might deforest early to guarantee tenure (Southgate *et al.*, 1991) or push forward monetary rewards (and mining soil nutrients) in fear of appropriation (Alston *et al.*, 1995). With open access, farmers would be expected to degrade the resource until agricultural profits were zero everywhere – the familiar tragedy of the commons (cf. Angelsen, 1999, citing Angelsen, 1994).

In the frontier area under study here, both inherent quality of soils and its response to management have emerged as central to land-use policy – critical factors in the dynamic that leads to deforestation for agriculture by small-scale farmers. Farmers in the area must work within the realities of difficult-to-obtain credit (so they largely self-finance any investment) and scarce labor (so there are limits to hiring even with capital in hand) in making land-use decisions. In other words, they function within the more imperfect market setting (Vosti *et al.*, 2001b). Yet the frontier area itself is developing in terms of markets and roads, and improving their lot by using land and labor available to produce sellable items was the objective articulated by interviewed farmers, even when they were prevented by circumstance from doing so.

This study takes that objective as a starting point, in keeping with much work applying constrained optimization to rural households in developing country settings (e.g., Sadoulet and de Janvry, 1995; Deaton, 1997, and, for the tropical forest margins, Angelsen and Kaimowitz, 2001). Given the spread of markets in this frontier area, and the fact that only under severely isolated and near subsistence conditions would farmers act in ways counter to those expected to raise profits (Angelsen, 1999), this study focuses on a farm well-situated *vis-à-vis* what local markets exist, and a farmer aiming for the highest possible net present value of consumption over time, accounting for constraints faced.[2]

While touching on other aspects of land quality in the study area, this study focuses on soil fertility. It does so because soil fertility is the most serious – but not the only – soil-related problem farmers in the Amazon face (Koning *et al*., 1997), and has been central to the discussion on the potential for (and indeed the viability and extent of) agriculture in tropical forest zones. Indeed, evidence is accumulating for the Amazon (Embrapa, 1981; Smith *et al*., 1991; Roulet *et al*., 2000; Farella *et al*., 2001) and elsewhere (Bruijnzeel, 2004) that deforestation is causing increased erosion, thereby changing the concentration and composition of water-transported materials, and affecting a broad array of hydrological services. Assessment of erosion's effects on agriculture, however, is best handled by a model beyond farm level (see, e.g., Barbier and Bergeron, 2001). For this site, the relatively good soil cover provided by the dominant land use – pasture (Cordeiro *et al*., 1995) – should mitigate implications of not taking erosion into account (we return to this point in the conclusions).

To incorporate context-specific empirics into a theoretical framework and explicitly deal with the dynamics of the soil problem, this paper employs a linear programming model that integrates biophysical (tracking nutrients) and socioeconomic (relative prices, regulatory environment, labor, and capital constraints) factors in a constrained optimization framework. It contributes to the literature in bioeconomic modeling incorporating soil agronomic potential (e.g., Burt, 1981 for the Northwest US; Barbier and Bergeron, 2001 for villages in Honduras), but focuses on decision making at the farm level, where imperfect markets create on-farm competition between agricultural activities for limited labor, land, and capital.

In general, such linear programming models offer the advantage of an intertemporal optimization framework under well-delineated production, resource, or other (sometimes evolving) constraints – using numerical analysis to shed light on otherwise intractable problems (often without closed form solutions). The mathematical framework facilitates integration of established or hypothesized relationships on both biophysical and economic sides, and allows model calibration using real-world data. Quality of model results, however, as in other types of analysis, depends on how well the hypothesized inter-relationships capture the real processes of interest (an appropriate model scope, proper specifications, no key omissions). And, as in other models, the more types of processes modeled, the greater the opportunity for measurement or conceptual errors to enter (and perhaps compound each other) in model results. Moreover, relationships observed and valid for one range of values may not hold if

[2] Other work, including work on land use in Brazil (e.g., Costa and Rehman, 2005; Evans *et al*., 2001), looks at effects of additional smallholder objectives, still acknowledging the role played by economics and optimization. Angelsen (1999) explores how alternative characterizations of household objectives in tropical forests can be formulated within a constrained optimization framework by altering the form of the objective function (farmer preferences) and the nature of market and other contextual constraints.

conditions change radically. For these reasons, sensitivity analysis on model parameters and initial conditions is considered vital to the assessment of model accuracy, and care must be taken that simulated scenarios reasonably take place within the ranges of values where the hypothesized relationships hold (Ruben *et al*., 2001).

For the setting of smallholders in the western Brazilian Amazon, a simulation model grounded in empirics from farm survey data complements often cross-sectional regression analyses. Because they usually must rely on snapshots in time or unchanging aspects of soil quality, these analyses leave key questions unanswered about the role of soil quality and degradation in the deforestation process. This is the case both for regressions with a strong theoretical underpinning (e.g., Pfaff, 1999) and reduced form formulations that seek patterns in the data (e.g., Andersen *et al*., 2002).[3] Cross-sectional regression results from this western Amazon site, for instance, found the relationship between soil quality and land use varied by soil type, suggestive of but not definitive to a technology-mediated link (Vosti *et al*., 2002).

Such studies need to take soil quality as unchanging, and look for outcomes consistent with hypotheses. The linear programming approach allows a look at impacts of different soil type as well as degradation over time, using real-world data while imposing a structure consistent with economic theory and biophysical science. The model here differs from other work that incorporates plot-specific soil degradation (e.g., Albers, 1996; Evans *et al*., 2001; Roebeling and Ruben, 2001) into deforestation studies in that it specifically accounts for differences across soil types, and leaves the farmer more flexibility to decide what degradation/yield trade-offs to accept (the other models either force farmers into a fixed recuperation period or rely on less specific models of the cost of nutrient depletion).

The next section outlines the study context. The section that follows describes the bioeconomic model, especially how it incorporates soil quality and degradation into land-use decisions. Next, a section presents and contrasts three model simulations – one each for low-, medium-, and good-quality soils – highlighting comparisons in deforestation, cleared land-use and technology choice, and household income, and discusses some specific sensitivity analyses along with model caveats. The paper ends with policy implications, and touches on how generalizable the findings are within the study area and more broadly.

Study context[4]

With small-scale farms ranging in size from sub-hectare plots to 200-hectare farms by Brazilian definition (IBGE, 1998), smallholder agriculture in the forest margins of the western Brazilian Amazon may seem anomalous to similar settings internationally. Yet the situations are not that dissimilar. The

[3] While less bound by theory, these formulations do embody author assumptions in the functional and variable forms chosen.

[4] This section (aside from the information on soils) borrows heavily from background material presented in Vosti *et al*. (2003).

government distributed sizeable plots (roughly 100 hectares) in colonization projects to poor migrants from about the 1970s as part of efforts to develop the Amazon (Mahar, 1989; Ozório de Almeida and Campari, 1995; Andersen *et al.*, 2002). They arrive generally unfamiliar with agronomic conditions, with relatively little labor or financial capital available to earn a living. Their land – soils and the forests on them – constitutes their greatest asset. Yet soils in the study area – judged representative of the western Brazilian Amazon (Avila, 1994) – have problems similar to those cited for the Amazon region more generally: low agronomic potential due to poor inherent fertility, shortages of essential nutrients, relatively high concentrations of exchangeable aluminum, and problems linked to phosphorus fixation (Alvim, 1982; Geraldes *et al.*, 1995).

The region's slash-and-burn agriculture is shaped by its two seasons. Forest is felled during the dry season (May to July), burned (in August or September) before the rainy season, then planted to annuals, perennials, or pastures. The burn transfers the forest's stored biomass to the soil, with the ash lowering soil acidity to make the replenished nutrients and organic matter more available to crops. The farmer usually plants annuals for one to three years after deforestation (Fujisaka *et al.*, 1996). With use of fertilizer virtually nonexistent in the study area, annuals take up nutrients from the forest burn, yields decline rapidly after the second year, and annual crop production on a given plot is usually abandoned after the third year. Sometimes the plot is fallowed for several years to regenerate biomass via secondary forest re-growth for a second cycle of slash and burn and annual cropping.

One of two land-use systems follows – tree cropping or pasture. Properly managed, both come closer than annuals to replicating the forest's nutrient cycle. Still, they too eventually require a fallow cycle or external inputs for continued production (Palm *et al.*, 1996). Perennials – usually bananas or coffee – must grow for several years before producing, with replanting approximately every eight years. Pastures take a year to establish and are often burned annually for weed and pest control. They must be replanted at intervals that depend on management decisions affecting the pace of degradation, including stocking rates, quality of the forest burn, frequency of pasture burning, and variety of pasture grass planted. With proper management, pasture life can extend well beyond ten years; on worse soils without adequate management, pastures degrade to the point of replanting or abandonment after about seven years. Farmers usually engage in dual-purpose cattle activities, growing a herd for milk then culling for beef cows past prime lactating/reproductive years (Faminow, 1998; Valentim, 2002). Most farmers in the study area opt to shift most plots to pasture rather than perennials. Table 1 presents mean values for selected household and farm characteristics, agricultural and extractive activities, and soil quality from field data collected from approximately 200 small-scale agriculturalists over the period 1994–1996 at one colonization project in each of the western Brazilian Amazonian states of Acre and Rondônia. The stratified random sample (described in Vosti *et al.*, 2002) included purposeful sampling using soil quality as well as time since settlement and market access.

Table 1. *Farm and farm household characteristics*

	Overall sample Mean values
Upon arrival	
Origin (per cent from South/Southeast Brazil)	57
Resources upon arrival	
# of months of supplies	4.5
# of individuals	5
Land quality (per cent of sample farms . . .)	
without limitations	30
some limitations	41
waterlogged	3
severe limitations	24
By 1996	
Household size (#)	6
Age of HH head (years)	46
Literacy of HH head (per cent able to read/write at remedial level)	47
Dependency ratio (dependents/household size)	45
Pension received (per cent of HHs)	37
Farm size (hectares)	76
Land use (per cent of farm in 1996 in . . .)	
forest	56
pasture	29
annual crops	4
perennial crops	6
secondary fallow	7
Land tenure (per cent having document recognizing presence on land)	81
Farm income (1994 value of total farm output, 1996 R$; 1US$ = 1R$)	R$3,448
Farm income sources	
cattle-based (per cent)	46
annual crops (per cent)	45
extraction (per cent)	10
Forest products (per cent of HHs extracting)	67
Herd size (1996)	32 head (23 animal units)
Off-farm labor activities (per cent of HHs involved)	40
Distance to market (travel time, in hours)	2.2
Ratio of wet season/dry season travel time	2.3
Commercialization of agriculture (per cent of producing HHs selling . . .)	
annual crops	33
cattle	40
milk	33

By the time of the survey, the family consisted of on average six individuals (with middle-aged household heads, many practically illiterate), with high dependency ratios, often including a pensioner. Potential capital (for investment and subsistence) as captured in value of output averaged almost R$3,500, or about R$575 per capita in the household.[5] Farms averaged 76 hectares, with just over half still in forest and the remainder mostly in pasture. Longer settled farms tended to have more pasture and less forest. Farms reflected the generally poor soils characteristic of the region, with only about 30 per cent of sample households on land that faced relatively minor soil-related limitations (fertility problems over time) to agriculture.[6]

Of sample smallholders, over half already had a land title, and an additional quarter had a document linking them to the land they cultivated. Just under two-thirds extracted forest products, usually brazil nuts, for about 10 per cent of value of total output (although the buffering role of forest products during crises can be critical, see Wunder, 2001). By contrast, ranching contributed an average 46 per cent of farm income, with a mean herd size of 32 head (23 animal units). One-way travel to market took a mean of two hours during the dry season but more than doubled during the rains. Still, about a third reported selling annual crops, 40 per cent sold cattle (and 30 per cent purchased cattle), a third of milk producers sold milk, and 40 per cent engaged in off-farm labor.

A more thorough chemical analysis on a subset of farms (in the sample or judged to be similar to farms in the sample, totaling 61 samples) from one colonization project – Pedro Peixoto, Acre – focused on soil characteristics important for agriculture. Table 2 summarizes results, with soils grouped into three categories ranked by agronomic potential.

Only in 'good-quality' samples is the balance of cations close to ranges recommended as optimal for agriculture. The poor-quality soil stands out for its low pH and (related) potential aluminum toxicity, but application of lime could greatly improve soil productivity. As already noted, soil amendments can correct for inherent soil infertility or other problems, but cost money and time, and can benefit weeds as well as crops. The bioeconomic model described next takes such trade-offs between biophysical and economic factors into account.

Model description

A linear programming (LP) model was developed to account for the biophysical and economic factors determining farmers' deforestation and

[5] Unless otherwise noted, all monetary units in this article are 1996 Brazilian *reais*; R$1 = US$1.

[6] Land quality categories were derived from soil maps in conjunction with Embrapa soil scientists. A given lot was characterized by the land quality type making up the largest share. 'Some limitations' included fertility problems and mild slope restrictions. 'Severe limitations' meant more serious fertility problems and severely sloped land (Vosti *et al.*, 2002). More information on chemical properties of sample soils appears below.

Table 2. *Three soil quality groups representative of Pedro Peixoto soils*

	pH	*P*	*K*	*Ca*	*Mg*	*S*	*Al*	*H + Al*	*CEC*	*V*	*m*
	mg/dm³		*cmolc/dm³*							*per cent*	
Poor	4.4	2	0.05	0.2	0.1	0.35	2.3	5.11	5.46	6.4	86.8
Medium	5.1	5	0.36	2.4	1.5	4.26	0.4	3.3	7.56	56.3	8.6
Good	6.6	7	0.67	4.4	1.3	6.37	0.1	1.3	7.67	83.1	1.6

Notes: [1] pH, measured on a scale that ranges from 0 to 14, refers to the level of acidity; pH values between 5.5 and 6.5 are considered ideal for crop growth (Islam *et al*., 1980); values below 4.5 signal a potential threat from (available) aluminum;
[2] P refers to levels of available phosphorus: low → fewer than 3 mg/dm^3, medium → 3 to 6 mg/dm^3, and high → more than 6 mg/dm^3 (Oliveira *et al*., 2000);
[3] K refers to levels of available potassium: low → fewer than 0.1 cmolc/dm^3, medium → 0.1 to 0.3 cmolc/dm^3, and high → more than 0.3 cmolc/dm^3 (Oliveira *et al*., 2000);
[4] Ca refers to levels of calcium available: low → fewer than 1.5 cmolc/dm^3, medium → 1.5 to 3.0 cmolc/dm^3, and high → more than 3.0 cmolc/dm^3 (Oliveira *et al*., 2000);
[5] Mg refers to levels of magnesium: low → fewer than 0.5 cmolc/dm^3, medium → 0.5 to 1.0 cmolc/dm^3, and high → more than 1.0 cmolc/dm^3 (Oliveira *et al*., 2000);
[6] S is the sum of the basic cations, available Ca, Mg and K;
[7] Al refers to levels of (exchangeable) aluminum resulting from soil acidity; toxicity begins at 0.3 cmolc/dm^3 (Raij, 1981);
[8] H + Al is, by definition, potential acidity (hydrogen and aluminum cations), an important indicator of the buffering capacity of soils (Tisdale *et al*., 1985; Fontes and Fontes, 1992);
[9] CEC measures cation exchange capacity and is an important indicator of the ability of soils to retain nutrients (and toxins) and make them available to plants, CEC = S + H + Al: low → fewer than 4.5 cmolc/dm^3, medium → 4.5 to 10 cmolc/dm^3, high → 11 to 30 cmolc/dm^3, and very high → more than 30 cmolc/dm^3 (Oliveira *et al*., 2000; Tan, 1982);
[10] V measures base saturation, the percentage of CEC contributed by Ca, Mg, and K, $V = (100 \times S)/CEC$: very low → lower than 25 per cent, low → 25 to 50 per cent, medium → 51 to 70 per cent, and high → greater than 70 per cent (Oliveira *et al*., 2000); and
[11] m measures aluminum saturation or the percentage of CEC represented by Al, levels above 50 per cent cause crop growth problems (Fassbender and Bornemisza, 1987).
Source: soil samples were collected and analyzed by Angelo Mansur Mendes and Tarcizio Ewerton Rodrigues. Samples were taken from land under different uses (e.g., forest, annual crops, perennial tree crops, pastures), but priority given to analysis of pasture and forest samples. The soil quality categories presented here were derived on the basis of results of analysis of this priority subset. Gômes and Carpentier (co-authors of this paper) generated soil quality categories. $N = 61$.

land-use decisions (described in detail in Carpentier *et al*., 2000; Vosti *et al*., 2001a; Vosti *et al*., 2002). This section lays out the models' inputs – initial conditions on the farm and in the farmers' socioeconomic environment, available production technologies, and biophysical parameters regarding soil and yield responses to these – as well as outputs (land use including deforestation rates and farmer incomes).

In the model, an archetypical household – derived using a subset of the field data described above – maximizes the discounted value of the family's consumption stream over a 25-year time horizon by producing for home consumption and sale, subject to various constraints. The constraints include household characteristics (including available labor and capital), aspects of the local market/regulatory environment, plus specific production technologies and their impact on soil productivity and its regeneration.

The model's initial conditions come out of sample data from the Pedro Peixoto settlement project, Acre. These farm households were clustered on the basis of characteristics exogenous to farmers' land-use decisions in the model – including soil type, distance to market, and time since initial land settlement. Of the several clusters (farm types) that emerged, averages for the *relatively well-situated farm type* in terms of access to markets were used as initial conditions to generate the model baseline. This choice, and the profit-maximization assumption underlying the model, were based on current trends in the area toward improved market access, and the fact that the model itself looks forward. The better market access assumption mitigates any effects of ignoring, as the model does, how consumption decisions in this imperfect market environment might affect a pure profit maximization strategy. Policy implications for these assumptions are taken up later.

The resulting archetypical farm spanned 60 hectares, with 17 already cleared, and had between one and two adult male family laborers. An additional between one and two adult equivalent laborers rounded out the household. Farms of medium-quality soil type dominated the cluster – soils with some inherent restrictions to agricultural productivity (fertility problems, and/or mild slope or rockiness). The model assumes that soil type is homogeneous over the entire farm. In the baseline, input and output prices from 1992–1993 (just prior to the 1994 survey) and a 9 per cent discount rate apply over the entire time horizon. Like other model parameters, these can be varied to perform sensitivity analysis or test impacts of alternative scenarios, as explored below.

For most production activities, the model identifies three technology levels (v1, v2, v3) ranging from the most prevalent v1 traditional systems (no purchased inputs) to v3 experimental systems (substantial use of purchased inputs) at or near the stage of on-farm trials and some initial adoption. Production systems include annual cropping (rice and corn separately or intercropped, and a later bean crop), perennials (including manioc in the context of the model, since it stays in the ground over a year, but also coffee and bananas), and pasture (with different types of seed and management systems, and levels of herd management) for cleared areas, as well as brazil nut extraction from forest areas. The technology describes inputs required and outputs expected per unit area per soil type subject to available nutrient levels (discussed below).

The model mimics the market/regulatory environment through its treatment of on-farm resources and by restricting some input and product flows on/off farms. To reflect difficulty obtaining credit, the model includes only within-season credit for consumption. On-farm investment is self-financing. The model reflects regional labor scarcity by imposing limits (15 man-days per month) on sale and hire of labor. Because the region has limited dairy processing capacity, quotas (averaging 50 liters a day over the course of each season) constrain milk sales. The model captures practical implications of Brazilian forestry policy as applied at the time of the survey: small-scale farmers do not harvest timber from their forested land (due to cumbersome certification) and ignore a policy mandating that 50 per cent (then, currently 80 per cent) of the farm remain forested (since farmers routinely surpassed this limit without penalty). The model does not account for risks (price, production, health among them) faced by smallholders, so provides an optimistic (certainty-based) view of agricultural production.

Perhaps most relevant for purposes here, the model differentiates between yield after forest clearing (and burning) for the three soil types, accounting for soil degradation or recuperation. It tracks available soil nutrients (measured in kilograms of nitrogen, but reflecting the relative presence of other nutrients important for plant growth, e.g., phosphorus and potassium) in cleared land. It gauges the nutrient effects of slashing and burning primary forest, producing and harvesting crops, growing secondary forest fallow (with complete recovery of forest nutrients in seven years, and eight years for retired pasture to recover the nutrient level of year 3 fallow), and applying fertilizer. Nutrients available on cleared land are pooled for purposes of planting decisions. The model then imposes a product-specific yield penalty (similar across soil categories) if soil nutrients available for annuals and perennials fall short of requirements for achieving expected crop yields. Application of nutrient deficit to each product is itself optimized by the model, so the yield penalties imposed are perhaps more widespread, but less exacting on any one crop than on actual farms. Yield performance across soil types and over time, plus parameters to track nutrients through forest growth, slash and burn, and crop uptake were obtained via consultation with local experts, soil scientists, and farmers' groups.

Land under pasture is removed from the nutrient calculus since degradation (and loss of carrying capacity) is built into each technology. Pasture degradation (over a 20-year cycle) and fallow nutrient recuperation are assumed the same across all soil types. Soil-quality-invariant pasture productivity may be a viable simplification: research has found pasture degradation unrelated to soil chemical make-up (Muller *et al.*, 2004), or similar across soil categories as regards nutrient (specifically phosphorus) availability (Numata *et al.*, 2003). In addition, recent research in Acre has found soil drainage rather than fertility poses the most serious threat of pasture death (Amaral *et al.*, 2004), although low-quality soils cost more to re-establish (Valentim and Andrade, 2004). The assumption about soil-quality-invariant secondary fallow productivity could influence model land-use results, though given the small area dedicated to forest fallow, the effect is likely small. Over a longer time horizon (beyond the disappearance of primary forest) as fallow's role as a nutrient source grows, differential fallow recuperation rates could matter more.

Table 3 reports peak yields for each crop – corresponding to first year for annuals, and third to fifth year for perennials (depending on technology level) – resulting from the participatory assessment.

Specific plots of land cannot maintain these yields without v3 technologies to correct soil chemical imbalances and replenish soil nutrients. The technologies most commonly encountered in the field (v1 and v2 technologies) experience yield declines on a given plot with repeated planting. Without external inputs, a (v1) rice/corn bean rotation's yields decline in year two before precipitously falling off after year two for rice and beans, and after year three for corn, as Figure 1 shows (using medium-quality soil figures). Similar yield drop-offs occur for v2 technologies from their higher first-year yield base.

Model simulations

Model baseline

Figure 2 depicts the changing land cover (including forest loss) generated by the model for a 25-year time span for the archetypical small-scale farm (with medium-quality soils). Forest declines steadily, disappearing in about year 25, despite small revenue from brazil nut extraction. As forest falls, pasture rises, eventually occupying about 85 per cent of the farm, in line with sample descriptive statistics for farms of different ages. The household maintains about 8 per cent of the farm in annual crops and about one hectare in (the 'perennial') manioc (although not the same piece of land in either case). Secondary fallow weaves into and out of the baseline, becoming more significant as forests disappear. At no point does the model farmer find it profitable to retire (degraded) pasture or invest in chemical fertilizers for annuals or perennials, even with a sufficient cash reserve to purchase them. Farmers instead alter cropping patterns to circumvent soil fertility problems, shifting land into pasture and deforesting more for crops. Policy experiments presented below will suggest whether initial soil quality differences within the range found in the study area might prompt smallholders to shift from adapting land uses to fertility constraints, perhaps to purchasing fertilizer.

The model suggests an ongoing capitalization process by which farm households use forests – by felling them – to pull themselves toward greater financial security through self-financing investments. In the baseline, the household consumes a net present value (NPV) of R$50,635 over the 25-year period. Savings early on permit investment to boost production and consumption later. Expanding pasture requires large investments (negative savings) in years 5, 9, and 11. Profits plateau at about year 13 at approximately R$9,000 per year, declining after the end of the 25-year time horizon presented here.

Dual-purpose dairy/beef cattle production accounts for pasture's dominance in the baseline, with dairy production beginning early and continuing throughout. Once the milking herd is established (by year 10),

Table 3. *Peak-year crop (annual) yields, by technology level and by soil quality*

	Monoculture[1]			*Intercropped*[2]	
	v1	*v2*[3]	*v3*[4]	*v1*	*v2*
rice (kg/ha.)					
poor	–	1,500	2,600	620	1,082
medium	–	2,000	2,900	799	1,300
good	–	2,500	3,000	992	1,642
corn (kg/ha.)					
poor	–	2,000	3,200	488	800
medium	–	2,500	3,300	640	900
good	–	3,000	3,400	800	1,000
beans (kg/ha.)[5]					
poor	–	500	1,300	202	500
medium	–	800	1,400	390	800
good	–	1,000	1,500	565	1,200
manioc (metric tons/ha.)[6]					
poor	12.0	13.6	–	–	–
medium	13.6	15.2	–	–	
good	14.4	17.6	–	–	–
coffee (kg/ha.)[7]					
poor	500	–	3,480	–	–
medium	970	–	3,600	–	–
good	1,200	–	3,800	–	–
bananas (bunches/ha.)[7]					
poor	797	–	1,023	–	–
medium	797	–	1,023		
good	797	–	1,023	–	–

Notes: [1]v1 monoculture technologies are neither practiced by small-scale agriculturalists in the sample area nor selected in the model simulation, and have been omitted from the table.
[2]v3 intercropping technologies are not practiced by small-scale agriculturalists, nor is their development contemplated by agricultural researchers; they do not appear in the table.
[3]v2 monoculture and intercropped technologies make use of some pesticides, primarily insecticides, but do not use chemical fertilizers.
[4]v3 monoculture technologies make use of both pesticides and chemical fertilizers, adjusting use of the latter to compensate in part for inherent differences in soil quality.
[5]Monoculture bean yields refer to beans following corn or rice alone; intercropped refers to bean yields following rice/corn intercropped.
[6]Manioc harvests are roughly evenly spread out over seven months.
[7]Yields for coffee and bananas begin low, increase over time, then drop off (more quickly for v1 than v3 technologies). Coffee and banana peak yields are in year 3 for v1, year 4 for v3 banana, and year 5 for v3 coffee.
Source: Productivity parameters were generated on the basis of meetings with farmers' groups, extension agents and agricultural researchers. v1 intercropped parameters were estimated from field data then verified by meeting participants.

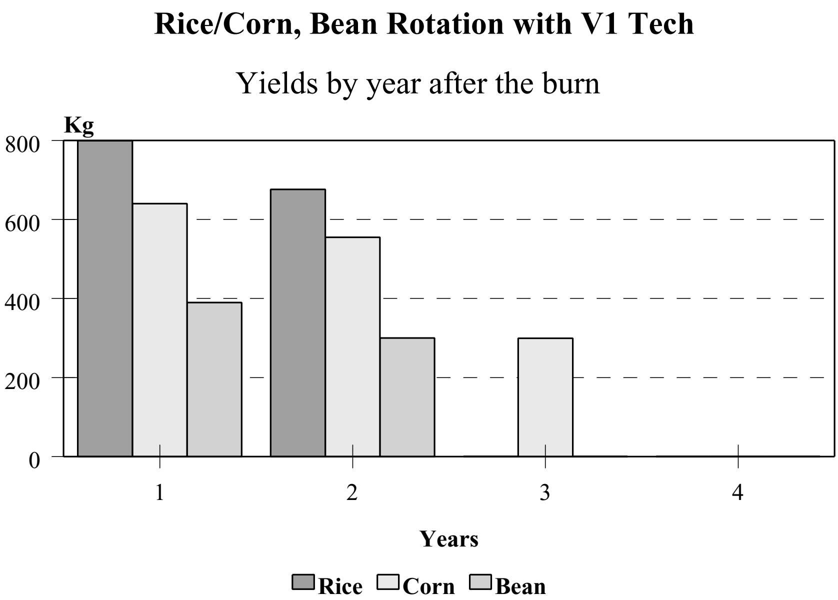

Figure 1. *Per-hectare yield declines for intercropped annual crops on medium-quality soil, using v1 technology*

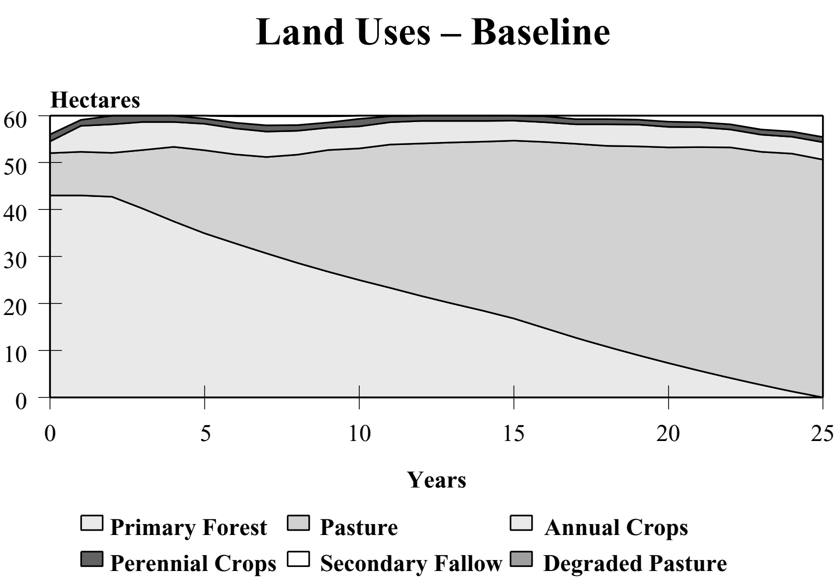

Figure 2. *Baseline land uses, by year*

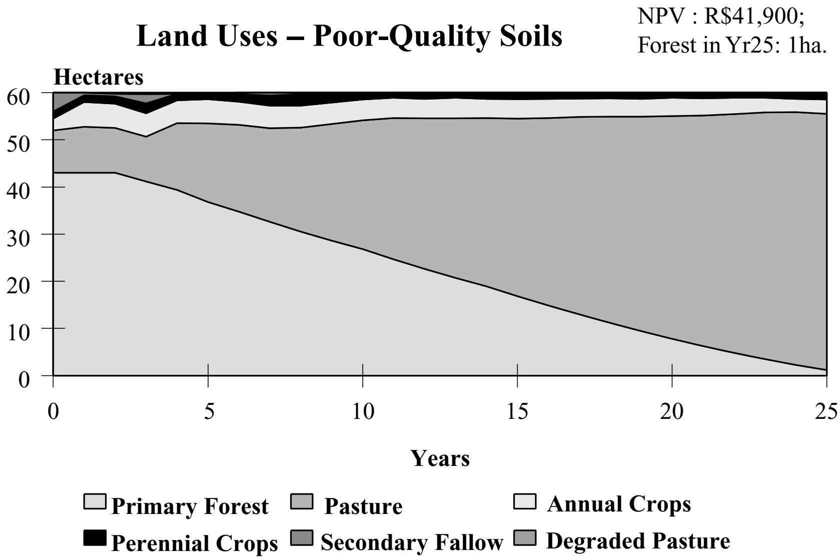

Figure 3. *Land uses with poor-quality soils, by year*

dairy production provides roughly 77 per cent of income, and occupies an average of 42 per cent of available household labor most months. Beef production emerges as a second cattle activity in year 9; its contribution to income plateaus at 25 per cent in year 18, although it occupies (on average) just 4 per cent of household labor. This dominance of dual-purpose cattle production systems has occurred at the study site; milk production in Acre shot up in the 1990s from 21 to 41 million liters per year, then nearly doubled in a single year (Embrapa Gado de Leite, 2002). Other Amazonian states also saw impressive growth in milk production – substantial proportions were believed to change hands without processing (Embrapa Gado de Leite, 2002) – as the cattle herd in the Legal Brazilian Amazon increased from 26.3 to 57.4 million head over the period 1990 to 2002 (Valentim and Andrade, 2004).

Differing soil quality

Using the yield coefficients and the yield drop-off and soil recovery functions described above (but with other parameters as in the baseline), model scenarios for poor- and good-quality soils were generated.

Figure 3 presents land-use categories (and deforestation) for small-scale farms located on poor-quality soils, reflecting an assumption of ample initial cash to start the process. Figure 4 presents results for good-quality soils. Both scenarios result in just slightly slower deforestation than in the (medium-quality soil) baseline. The farmer adapts to lower-quality soils not by applying chemical fertilizer, but, compared to the baseline run, by shifting a bit of land out of annuals and secondary fallow into pasture. NPV of consumption over the 25-year simulation time horizon drops by

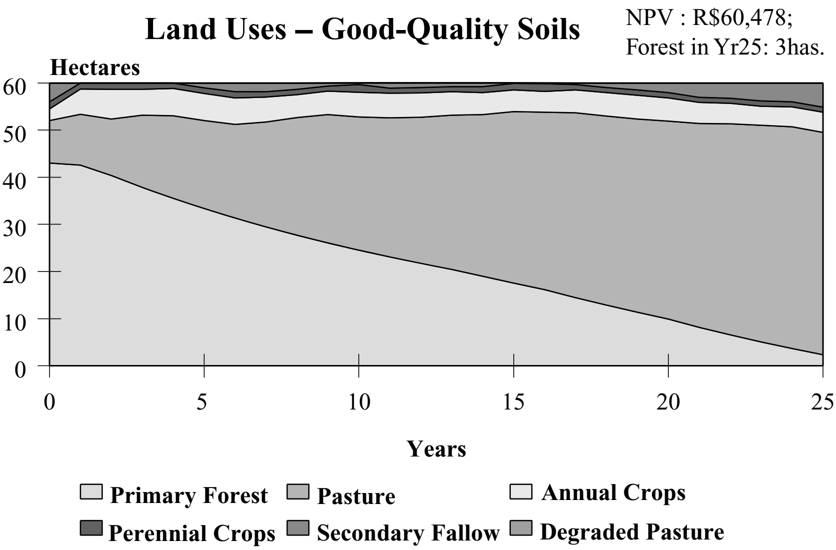

Figure 4. *Land uses with good-quality soils, by year*

17 per cent (to R$41,900). In the case of good-quality soils, the shift is in the other direction – slightly less pasture, and slightly more in annual cropping and fallow, with NPV of consumption 20 per cent higher (at R$60,478) than in the baseline.

Initial runs of the model for poor soils yielded a nonviable situation with the household hovering at the edge of subsistence (around 20 per cent of baseline NPV of consumption). Although the poverty translates into substantially more forest left in year 25 (16 hectares), these forest savings vanish (and NPV of consumption rises dramatically) with small infusions of additional cash at the outset of the process. Similar cash injections for the medium- and good-quality farms, in contrast, have only minor effects on land-use and income trajectories. For the poor-soil farm, the extra cash in effect launches the smallholder on the faster forest-to-pasture capitalization path for a viable farm. That it would be available is in keeping with the focus here on the well-situated farm *vis-à-vis* markets (policy implications of this conjecture are explored later). Once initial cash is sufficient to launch the trajectory, the marginal forest and welfare effects of additional cash injections quickly diminish (so the poor-soil farm becomes more like its better-soil counterparts in this regard).

Discussion of soil quality results

All soil quality scenarios share similar deforestation patterns: the forest on farm land disappears within 25 to 30 years for the viable farm. Farmers with good-quality soils deforest at nearly the same rate as those with poor-quality soils, with both deforesting only slightly more slowly than the baseline farmer with medium-quality soils.[7] This suggests that resource poverty – in poor- vs. medium-quality soils in this case – can brake deforestation. The point is underscored by the fact that households without cash to establish viable farms on poor-quality soils save substantial amounts of forest. Results also suggest that additional cash would translate more readily into additional forest lost when the extremely cash poor settle on farms with poor-quality soil (although in the case of farms with good market access, this pairing is less likely to last/be observed). Good-quality soils, in contrast, allow shifts of on-farm resources (notably labor) to take pressure (albeit a tiny amount here) off the forest.

Pasture dominance also marks all scenarios – underlying conditions make this the highest value land use to the labor-constrained farmer regardless of soil quality. As base soil quality improves, however, the farmer does shift land use, taking advantage of the extra nutrients by putting more land into relatively more nutrient-demanding annual cropping, supported by more land set aside in secondary forest fallow to recuperate nutrients. In none of the scenarios did farmers opt to purchase and apply chemical fertilizer despite capitalization that put this within reach. In fact, the impact of soil quality changes was much more substantial on incomes than on land use; good-quality soil generated a 44 per cent income premium over poor-quality soil.

Differing initial conditions and policy scenarios

The simulations run to examine model sensitivity to alternative initial conditions and policy options underscore the lessons from the three soil simulations: pasture's dominance is robust to many circumstances, and labor scarcity has a critical mediating role between available on-farm resources and resulting land use via relative and absolute factor intensity of alternative technologies (Vosti *et al.*, 2002; Vosti *et al.*, 2003). Table 4 summarizes results – farm household income, and area in forest and pasture year 25, for each simulation, all assuming medium-quality soils (some also presented in Vosti *et al.*, 2003).

Results for alternative initial household and market conditions highlight labor (vs. capital) availability's importance to land use under baseline conditions. Cutting off access to hired labor directly by not allowing hiring or indirectly by dramatically increasing the wage affects deforestation, with method mattering for incomes. If hired labor is unavailable incomes fall and nearly 15 hectares of forest remain in year 25. A quadrupling of the wage rate saves nearly the same amount of forest, while increasing farm incomes substantially over the baseline: the household makes use of its earning power off farm and reduces agricultural activities at home. Banning sale of household labor – which reduces capital available but does not appreciably affect labor available on farm – amounts to little in the way of forest saving and slightly reduces incomes. Even with four times more initial cash on hand than in the baseline, farmers with medium-quality soils end up with

[7] This result holds whether or not the farmer with good-quality soil is given extra initial cash to match the boost given the poor-quality soil farmer.

Table 4. *Summary of results of model scenarios: medium-quality soils*

Alternative model scenarios	*Farm household income (NPV, R$)*	*Forest remaining (Hectares in year 25)*	*Area in pasture (Hectares in year 25)*
Baseline scenario	50,635	0	50.6
Alternative initial HH and market conditions			
No hired labor (sale of HH labor allowed)	45,454	14.6	40.4
Quadruple wage rate (hiring and sale of HH labor allowed)	69,431	13.1	42.2
No sale of HH labor (hiring of labor allowed)	48,437	1.15	46.8
Quadruple cash available	52,720	0	50.8
Alternative policy/ technology scenarios			
Low agricultural technology	9,020	10	31
50 per cent rule enforced	44,160	30	25
100 per cent fertilizer subsidy	77,115	7	44

Source: Modified from Vosti *et al*. (2003).

basically identical income, deforestation, and pasture outcomes. As noted earlier, good-quality soil farmers with extra cash had similar outcomes, but on poor-quality soils, slightly higher cash endowments quickened the establishment of viable farms and increased deforestation. Additional cash endowments above this threshold level had little effect on deforestation rates.

Changing policy options *vis-à-vis* the baseline underlines trade-offs between income and forest savings. The low-technology scenario mimics the situation of a poor farmer who never adopts modern technologies. By the criteria laid out above, this farming operation – at less than 20 per cent baseline consumption NPV – would not be viable. While survey results do not suggest that lack of knowledge of technologies is a serious constraint, financial distress due to risks not in the model could delay accumulation of financial means to adopt technologies, leading to lower income levels. As in the poor-quality soil simulations, inability to invest slows the pace at which forest falls. A simulation enforcing the forestry policy prohibiting clearing more than 50 per cent of farm property indicates that, with all technologies available, the forest savings would mean a 13 per cent income decline. In the last policy scenario, a 100 per cent fertilizer subsidy still does not substantially shift land use: year 25 sees only seven hectares left in forest, similar land in pasture and annuals as in the baseline, but less secondary forest fallow (because of the free alternative nutrient source), and a 50 per cent higher NPV. This result points to demand for land rather than nutrients driving deforestation in this forest margin setting (Vosti *et al*., 2002). As with nutrient shifts via soil quality, the main impact of a fertilizer subsidy is on incomes, not land use. Still, as on good-quality soils, fertilizer on medium-quality soils slightly retards deforestation.

Additional sensitivity analyses demonstrated the robustness of findings. Changes in the discount rate had only slight effects on deforestation rates and household income. Increasing distance to market slowed deforestation somewhat and lowered income, without changing the qualitative results. Model results were more sensitive to belonging to a dairy cooperative – with no outlet for dairy, deforestation rates and income both dropped (but soil scenarios using this as a baseline revealed the same patterns described above). Given the rise in dairy production in the region (roughly in step with increased regional demand – see Faminow, 1997), this lower bound is not likely to reflect reality on the ground. Without a dairy option, moreover, there is a strong possibility that other, more profitable activities would have emerged than suggested by merely the current technology set minus dairy. An additional simulation with an experimental system of sustainable managed forestry (details in Vosti *et al.*, 2003) saves about 10 hectares of forest by year 25, while increasing incomes by just over 8 per cent (*vis-à-vis* the baseline), but would require legislative changes and institutional innovations for enforcement.

Taken together, the model simulations presented here and elsewhere (Vosti *et al.*, 2002) suggest that deforestation and land-use outcomes are quite robust to reasonable ranges of potential changes in policies as well as economic and market conditions. Still, several important caveats apply. As noted earlier, this type of modeling exercise aims less to predict future outcomes than to highlight the dynamic that drives current behavior. In doing so, it relies on specific assumptions, here shaped by the model's forward-looking nature in a setting of generally developing markets and rising incomes. Namely, households well-situated *vis-à-vis* markets maximize discounted streams of consumption, do so with knowledge of input and output prices over the decision time horizon, without exposure to production or other risks unaccounted for in the calculation of average yields. Market conditions, technological options, and farm size, moreover, remain stable over the time horizon. While each of these assumptions will not strictly hold, we expect they do capture the underlying rationale pushing farmers to deforest under current conditions.

Even if risk or other causes led to poverty or lack of access to technology that slowed deforestation, these conditions (as argued above in the discussion of viable farms on poor soils) will likely ameliorate *on a given farm* over time due to improved market access. The poor may be displaced to cities or further into the forest in the process – one of several issues that lie beyond the scope of farm-level analysis, yet have broad policy implications (returned to in the concluding section). Other such off-farm effects of farm-level behavior include production's effects on local market conditions (e.g., of a general equilibrium nature) or ecological services (e.g., via lost forest or erosion). Some of these effects could have feedbacks to farm-level behavior. Other work does look at ecological factors (e.g., Albers, 1996 or for this site Vosti *et al.*, 2002), and, in other contexts, examine economic feedback effects through hierarchical models that nest economic levels (Ruben *et al.*, 2001). Also beyond the scope of this model are important longer-term considerations regarding agricultural development in the area, including technological advance or emergence of a non-farm sector (that could take pressure off forests).

The specific functional structure used to embody model assumptions can also affect results. The model critically assumes that real-world biophysical and technological parameters can be adequately approximated through linear relationships. This assumption can be violated in a couple of ways. If there are non-linearities in these relationships (increasing returns from technologies, for example, or soil degradation floors beneath which soil nutrients become far more difficult to recuperate), the model would not accurately depict farmer responses. The argument here is that, within the ranges of the calibrated model, the linear approximations should suffice to give clear information on directions and magnitudes of behavior and outcomes in response to selected scenarios.

In addition, farmers face a fuller range of options than captured in technology packages for calibrating and adjusting inputs and drawing down natural capital. Size/computation constraints limit the modeler's capacity to reflect this reality, so the aim is to provide a wide enough variety of technological packages to pick up the main thrust of farmer choices in deciding how to use external inputs vs. natural capital. We have tried to do that here, but the possibility remains that, with a freer choice about how to use inputs on crops, or adjust stocking rates (degree of overgrazing), some model results could change (but again probably not qualitatively).

Conclusions and policy implications

Model simulations call into serious question a commonly held notion that providing an alternative to forest nutrients will slow the pace of deforestation, showing instead that the most important and largest impact of soil quality differences is on not land use but income. Improvements in soil quality and even free provision of fertilizers do not override the strong financial incentives favoring pasture that result in conversion of all farm forest within about a generation, highlighting that land hunger rather than a need for nutrients drives farmers to fell primary forest. That said, the model does suggest that farmers adapt to differences in soil quality, and not by purchasing fertilizer (even when they can) but by adjusting the product mix and production technology in ways shaped by both relative prices and how various technologies use limited resources. Results suggest that mechanisms for adaptation vary by soil quality level, and in ways linked to available capital. Despite these adaptations, soil quality differences translate into large shifts in farm income.

A farm with good-quality soil generated a 44 per cent higher NPV of consumption over the 25-year simulation period than did an established, viable farm with poor-quality soil. Still, viable farms located on poor-quality soils can generate substantial income over the model's decision time horizon which compares positively to incomes earned in some urban and many rural areas of Brazil. This result undermines the argument that areas endowed with poor-quality soils, if set aside as reserves, would be easy to protect from invasion (*unless* sufficiently isolated from markets). An important caveat, however, arises from the fact that farmers on poor-quality soils need more cash on hand to set up a viable farm, even with reasonable access to markets. Hence, locating colonization projects on poor-quality soils runs the risk of exacerbating rather than alleviating poverty among cash-poor smallholders – but probably through their displacement, with little long-term impact on deforestation outcomes (although temporarily slowing its rate).

Simulations reveal a small 'U-shaped' pattern between soil quality and deforestation – farms with medium-quality soils deforest more quickly than those with poor- *or* good-quality soils. But the factors braking deforestation differ in better- vs. poorer-quality soils. Even viable farms with poor-quality soils are too cash/capital constrained to deforest all the land they would like to. Instead, they invest slightly more in the least nutrient-hungry land use – pasture. Farmers with good-quality soils have the cash/capital to deforest as much as the farm with medium-quality soils, but choose to deploy household and hired labor in ways that take advantage of the extra nutrients – they engage in slightly more annual crop production and secondary fallowing. Because regional labor is scarce and annual crop production relatively labor intensive, this means clearing (slightly) less forest.

The poor-soils group tells us something about poverty thresholds and deforestation (Reardon and Vosti, 1995); the better-soils group, about the importance of the specific technology and market environment to the impact of income growth on deforestation. Together, the differences suggest that policies for retaining forests may need to be tailored to specific resource situations. In our setting, market development suggests that the first braking mechanism – due to poverty – is disappearing over time. The second braking mechanism, independent of capital constraints, will likely persist longer. Still, this second effect would be expected to subside if and when local labor scarcity is alleviated.

From a policymaking point of view, the braking effect is slight in either case. That said, the results indicate that improved soil fertility could promote labor-led intensification via agricultural activities, and that labor-intensive agricultural technologies may slow deforestation somewhat. Perhaps more importantly as regards poverty alleviation policy, results indicate that the poor-soils group may suffer a broad precariousness of livelihood. Situations can arise (health problems in a malarial area or weather shocks, for example) that at least interrupt the (self-financing) trajectory indicated here, and throw vulnerable smallholders toward dangerously low income levels that could significantly retard deforestation. More capital to this group would likely increase rates of deforestation (*ceteris paribus*). While the results here highlight farms with reasonable market access, remote farms could suffer similar vulnerabilities.

In settings with poorly functioning markets (in this case, particularly for labor), specifics of available technology and factor endowment can make a difference to production and consumption outcomes. This paper points out how endowment of natural capital – in the form of underlying soil quality – can affect land-use decisions and (especially) income as farmers trade off profitability and degradation. Its contribution lies in demonstrating the ranges of effects for empirically based ranges of conditions. Insofar as other areas have other underlying conditions – biophysically and economically, and given the importance of these specifics to direction and magnitude of deforestation and income results – this study's results cannot be generalized to other areas without careful consideration. Still, the study does make a broader point for research and policy – that where many factors converge to create an overwhelming rationale for the current land-use trajectory (as with the forest-to-pasture trajectory here, and other forest-felling patterns elsewhere), it will be difficult to find and/or implement a single policy lever (e.g., nutrient substitutes) to alter that trajectory. And, the potential is for the qualitative results to apply in a broad swath of the Brazilian Amazon where the pasture dynamic does appear under the range of soil qualities explored here.

The results may then seem to point inexorably toward a win (poverty)–lose (forest) future, but that overstates the point. Just as poverty eradication is by no means assured without continued policy attention, so is lost forest by no means a foregone conclusion. The purpose of the simulations is not to predict the future, but rather highlight the mechanisms likely to be driving the dynamic. For timeframes under discussion here, regional modeling is needed to help bridge the research gap between work such as this one that focuses on a particular farm-level dynamic, and regional deforestation studies (e.g., Pfaff, 1999; Faminow, 1997; Andersen *et al.*, 2002; Chomitz and Thomas, 2003 for the Brazilian Amazon) that account for landscape features such as topography and roads.

Continued development on longer time scales could bring changes both favorable and unfavorable to forests. Improved market access or spatial expansion of markets could hurt forests, as could greater movements of labor into the area. On the other hand, increases in wages, broadening of off-farm opportunities, or emergence of markets in environmental amenities (such as sequestered carbon) could take pressure off forests. Technological change, as we have seen, could work in either direction. The search for alternative nutrient sources (in fallow, purchased inputs, or more remote forests) to local forests could intensify as biomass in forests runs out locally – with unclear implications for additional deforestation.

These kinds of more sweeping changes (no less their effects) lie beyond the scope of a farm-level model to forecast, but not policy to consider. Farm-level models such as this one can, on the other hand, suggest likely farm-level reactions to precisely specified changes, and steer policymakers away from apparently attractive (yet ultimately ineffective) solutions, such as a cheap nutrient substitute to slow Amazonian deforestation.

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