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Modelling land use, deforestation, and policy: A hybrid optimisation-heterogeneous agent model with application to the Bolivian Amazon*

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Abstract: We introduce a hybrid simulation model ('SimPachamama') designed to explore the complex socio-environmental trade-offs of alternative policy bundles and policy sequencing options for stemming deforestation and reducing poverty in tropical countries. Designed and calibrated to the initial conditions of a small forest village in rural Bolivia, the model consists of: (a) an optimising agricultural household module of heterogeneous agents that make individually optimal land-use decisions based on factor endowments and market conditions; (b) an encompassing general equilibrium 'shell' module that endogenously determines wages and links the agricultural labour market and rural-urban migration rates; and (c) a novel user-controlled policy-maker module that allows the user to make 'real time' choices over a variety of public and environmental policies that in turn impact land use, welfare, and migration. Over a 20-year simulation period the results highlight trade-offs between reductions in deforestation and improvements in household welfare that can only be overcome either when international REDD payments are offered or when decentralized deforestation taxes are implemented. The sequencing of policies plays a critical role in the determination of these results.

Key words: Simulation, Bolivia, deforestation, land use, policy, REDD

JEL codes: Q23, Q28, Q56, R14

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1. Introduction

For decades, deforestation and forest degradation in tropical nations have reduced supplies of forest ecosystem services (MEA, 2005; FAO, 2010). These losses have had consequences at all scales, from local to global. Forest users with incomes and livelihoods dependent on, e.g. watershed services, have experienced adverse effects on their welfare. Emissions of carbon dioxide from deforestation and forest degradation influence the trajectory of anthropogenic climate change with welfare implications for future generations across the globe (Stern, 2008). Yet, policies which aim to conserve forests, such as protected areas, can also adversely affect the welfare of the forest-dependent poor, for instance, by restricting their access to natural resources (Barrett et al., 2011). Evidence is also emerging of how measures to improve welfare, such as anti-poverty programs, can induce environmental change, for example deforestation through increasing the local consumption and production of agricultural commodities (see Alix-Garcia et al., 2013).

In response, policy makers have increasingly sought to design interventions which not only aim to conserve forests but also improve the incomes and livelihoods of forest users (e.g., see Merger et al., 2011; Ollivier, 2012; Groom and Palmer, 2012). Targeted towards agents of deforestation, interventions such as payments for environmental services (PES) and the provision of off-farm labour opportunities could, under certain conditions, enhance their welfare as well as conserve forests (Groom and Palmer, 2010, 2014). Though multiple impacts are rarely evaluated together, a growing body of empirical research suggests variable outcomes from such policies (e.g. Shively and Pagiola, 2004; Groom et al., 2010). Beyond these effects, where external interventions necessitate public and/or private funding, there are also likely to be wider policy and welfare implications that may only be observed in a general equilibrium setting.

In this paper, we examine potential trade-offs in policy outcomes with a focus on two design features that help to better understand dynamic policy interactions: 'policy bundles' and policy sequencing. The former refers to combinations of policies that all, to some extent, impact on land-use decision making while the latter refers to the order in which policies are implemented. We incorporate these two features into a landscape- (or village-) scale model based on the structural, cultural and institutional features of a typical Bolivian frontier forest village, and we allow the model user, in the role of a local policymaker ('the Mayor'), the opportunity not only to implement policy bundles but also to react to the consequences of her policy choices over time. Thus, policy parameters can be changed and new policies can be implemented.

Our model is best defined as 'scenario-based' with 'coupled components' (Kelly et al., 2013). Specifically, in common with popular complex agricultural simulation models, such as AgriPoliS (e.g. Happe et al., 2009) and MP-MAS (Schreinemachers and Berger, 2011), the simulation comprises distinct 'modules' of submodels that each perform a specific role. First, a farm household module enables agents (households) to make decisions about agricultural land use and labour allocation, and includes separate crop and cattle components. The crop model builds on partial equilibrium models of the household (e.g. Angelsen, 1999; Ferraro and Simpson, 2002; Groom and Palmer, 2010, 2014) and models of land use allocation (Groom et al., 2010); Pascual and Barbier,2007; and Shively and Pagiola, 2004) to simulate the optimizing labour and land use decisions of heterogeneous farm households given their specific constraints and community wide attributes. Household decision making in the cattle submodel follows more heuristic rules that are consistent with insights gleaned from qualitative fieldwork in the region and reflect the special cultural significance of cattle ranching and local preferences for using cattle as a savings vehicle.

Second a state-space controlling ‘shell’ module defines the dynamics of the evolving physical and economic landscape in which the community of heterogeneous farm-households reside, endogenously adjusting wages to local labour market conditions, growing the cattle herd at a natural reproduction rate, and determining net migration to/from the city. Finally, in a novel contribution that is, to the authors’ knowledge, unique to the simulation modelling literature, a third policy maker (or ‘Mayor’) module observes real-time information on community well-being, deforestation, macroeconomic conditions and the Mayor’s budget (all provided by the shell module), and can then adjust a range of policies to try to reduce deforestation and improve welfare, subject to not running out of money. Policy interventions that can be adjusted throughout the simulated 20-year period of the model include ones with a development focus such as public investments made from the Mayor’s budget. These, in turn, impact welfare, productivity, and migration. Local land-use interventions with an environmental focus include conservation payments, international payments for reducing emissions from deforestation (e.g. REDD), and deforestation taxes that both impact land use and the Mayor’s budget, as well as welfare.

The model, called ‘SimPachamama’ (and freely available for download at: http://www.inesad.edu.bo/simpachamama/), is initialised and calibrated using rural household survey data from communities in the Beni river region of the Bolivian Amazonian frontier and is designed to be useful for students, scholars and stakeholders concerned about land-use change and social welfare in tropical forest settings. The model’s open source code is based on solid academic foundations and can be easily altered or augmented by students and scholars. The attractive, user-friendly interface can be easily understood and mastered by non-expert stakeholders, including policy makers and villagers/farmers.

Bolivia provides an appropriate setting for our model. It loses an estimated 300,000 hectares of forest annually[1], mostly due to the expansion of the agricultural frontier (Andersen et al., 2012). Furthermore, as in many tropical countries, annual per capita income remains below USD 5,000. Outlined in Section 2, the government’s approach has been to attempt to tackle both problems simultaneously, developing a programme for both reducing deforestation and rural poverty that relies on a broad set of interventions (INESAD, 2013).

Described in detail in Section 3, following the ODD+D protocol (Muller et al., 2013), the model is designed to reflect both the realities of the forest frontier and existing knowledge of socio-environmental trade-offs in such a setting. In theory, the model allows us to explore policy outcomes across an infinite combination of policy choices; in practice, the mayor reacts by adjusting policy choices as these outcomes evolve in response to previous choices. Over repeated simulations, the relative degree of success of different strategies becomes apparent to the mayor, the general results of which are shown in Section 4. This allows for experimentation and active policy learning in a simulated yet ‘real-world’ setting that can be easily adjusted to other settings. For researchers, by recording and comparing these policy sequences and outcomes a

[1] Killeen et al. (2007) and FAO (2010).

number of potential lessons have emerged that are theoretically coherent and potentially empirically testable. We further discuss these lessons and conclude in Section 5.

2. The Bolivian setting, methods, and calibration

2.1 Setting

Bolivia is relatively early in its forest transition, with more than 50 percent forest cover remaining and medium rates of deforestation (FAO, 2010). The country's 1996 land tenure reform law formally recognises indigenous communal properties (*Tierra Comunitaria de Orígen*, TCOs), and a new forestry law promoting sustainable forest management recognises some rights of private and communal landowners to forest resources. Nevertheless, work remains to finalise reforms and consolidate new property rights.

Bolivia was one of the first countries to develop a national REDD strategy. Between 2006 and 2010 its government advocated a strong role for forests in international climate change negotiations. There were more than 10 different, small-scale REDD projects and proposals in Bolivia, including some organised by local NGOs and indigenous groups. For example, the 'Subnational Indigenous REDD Programme in the Bolivian Amazon' was supposed to involve six million hectares in three TCOs, six municipal governments and national agencies responsible for forest monitoring.

However, in April of 2010 the political viability of REDD mechanisms was seriously challenged at the politically influential 'World People's Conference on Climate Change and the Rights of Mother Earth:'

> *"We condemn market mechanisms such as REDD (Reducing Emissions from Deforestation and Forest Degradation) and its versions + and + +, which are violating the sovereignty of peoples and their right to prior free and informed consent as well as the sovereignty of national States, the customs of Peoples, and the Rights of Nature."*

Although political causality is unclear, after the Conference the REDD preparation process in Bolivia stalled and the political environment grew quite hostile, with the Bolivian Government writing to the UNFCCC: "in all actions related to forest, the integrity and multifunctionality of the ecological systems shall be preserved and no offsetting or market mechanisms shall be applied or developed."[2] (Andersen et al., 2012).

The Government has instead started developing an alternative policy for reducing deforestation and rural poverty, called the *Joint Mitigation and Adaptation Mechanism for the Integral and Sustainable Management of Forests* (The Mechanism). While still in development, the Mechanism relies on a broad set of interventions, including both positive and negative incentives, as well as education and the active participation of local actors and policy makers (INESAD, 2013). In support of this effort UN-REDD has awarded Bolivia USD 1.1 million, and Denmark has also approved at least USD 26 million.

[2] FCCC/AWGLCA/2011/CRP.23, dated 4 October 2011.

At the same time, since 1996 Bolivia has actively pursued improved land tenure policies and as a result enjoys relatively strong and secure property rights, with a large proportion of plots officially entered in the land registry (INRA, 2007). For example, all of the households surveyed in this study (see below) either had clear legal title to their land, or were in the process of obtaining title. Thus, while insecure property rights has been a major obstacle to successful conservation policy in many developing countries (e.g. Streck, 2009; Sunderlin et al., 2009), the relative strength of land tenure in Bolivia allows us to assume that such policies can be effective and that these effects are observable.

2.2 Design and calibration

The Bolivian case thus presents a good opportunity to explore the dynamic complementarities and trade-offs between policies designed both to reduce deforestation and alleviate poverty. As the model is designed to reflect key institutional and cultural features typical of small agricultural communities in the Bolivian lowland Amazon frontier, it was designed, initialised, and calibrated based on observed behaviour of households in a typical village of Bolivian 'Colonos' (indigenous Aymara/Quechua migrants from the highlands). Households live on privately-held plots, initially assigned by the national government or bought from the local municipality, and engage in a combination of subsistence and market agriculture, cattle ranching, and some wage labour.

Broader ethnographic understanding of the area was based on previous research conducted by the two anthropologists involved in the project as well as two months of dedicated fieldwork in Rurrenabaque and the wider Beni region. This work provided significant, in-depth insight into the economic, cultural and environmental context of land use decisions of households. In addition the whole team of co-authors conducted a workshop in San Buenaventura (April 2012), with the participation of local farmers, cattle ranchers, loggers, teachers and the mayor of the municipality. During the workshop we met many local agriculturalists and a number of key model assumptions about land tenure, agricultural and cattle decisions, and labour supply and demand were discussed. Stakeholders and decision makers were also asked about their views on deforestation, economic development, and potential alternative policy options, such as access to finance, education, and migration to urban centres.

The model thus integrates many key characteristics of the local situation. Land in Colonos-type villages of the Beni river region is initially allocated to households by the government. Individual plots are of sufficient size that few families have put all of their land into agricultural production, nor have a desire to move to new land. While property rights in the region are reasonably well defined and secure, precluding the kinds of speculatory and defensive land use choices observed in some other Amazonian communities (e.g. Alston and Mueller, 2010), proof of land tenure is obtained only after some time (as resident agriculturalists). As a result we observe very few (if any) land market transactions taking place and there is, as yet, no sustained market for private land.

There is also a local reluctance to sell cattle. As in many Amazonian communities, cattle have a cultural and social significance that extends beyond the purely economic returns it provides. In particular cattle are seen as a source of social status and a primary form of household wealth formation and savings, as well as a hedge against future risk (Faminow, 1998; Birner, 1999). As a result households accumulate cattle steadily. In the local ideal it is only once a family has more cattle than can be sustained on the available land that excess cattle will be sold. For example, at our participatory workshop in 2012 agriculturalists explained that as the extensive form of cattle ranching practiced in this area can be practiced with minimal labour requirements, all the households accumulated cattle as their herd grew and eventually aspired to be pure cattle ranchers if they could. Thus in SimPachamama households choose cropping levels to maximise profits, but follow a more heuristic accumulation rule when it comes to cattle.

Finally, the model reflects a local labour market in which families first depend on their own labour for agricultural activities, although they can hire in extra wage labour if they need to and have available cash. Individuals may choose to work for others if they are not needed on their own land.

To quantitatively calibrate the initial parameters and features of the model we make intensive use of a household-level survey conducted in 2011 of 290 agricultural households from three such communities in the Beni river region on the Amazonian frontier (Leguia et al., 2011). Data from the Leguia et al. (2011) household survey was used for initial calibration of the model, including the distribution across all households of: household size, household wealth, household tenure (years on plot), property size, initial land use, and the size of the cattle herd. Data from the survey was also used for setting initial wage, cattle stocking and reproduction rates. Summary statistics of the main variables of interest are presented in Table 1. This table illustrates that the dominant non-forest land use is pasture followed by fallow and finally, agriculture. For model calibration and initialization of the simulation we choose observations only from 'Colonos' households.

TABLE 1 HERE

The insights and information gleaned from both the ethnographic fieldwork, the participatory workshop and the household survey were used to inform our decisions about model design and structure, and the overall performance of the model was to some degree externally validated by comparing simulated and actual outcomes. For example, Figure 1 shows the land use pattern generated during a typical run of model, while Figure 2 portrays a recent satellite photo (from Google Maps) showing the typical 'fishbone' pattern of land use from the Beni river region.

FIGURE 1 HERE

FIGURE 2 HERE

The local roots of SimPachamama also differentiate it in specific ways from other popular agricultural simulation models. For example, while a major component of some market models such as AgriPoliS (e.g. Happe et al., 2009) and MP-MAS (Schreinemachers and Berger, 2011) is an active land market, while, as we explained above, SimPachamama does not have a land market. Bolivian lowlanders do engage in both off-farm wage labour and in agricultural wage labour, and while there is some degree of both in- and out-migration, the region is still relatively isolated from broader labour markets. Thus, while in both AgripoliS and MP-MAS wages are exogenously given and fixed, in SimPachamama wages adjust each period in reaction to changes in local labour supply and demand, which in turn leads households to modify land use decisions. Finally, while both AgriPoliS and MP-MAS treat cattle as just another market commodity in a portfolio of potential land uses, our qualitative fieldwork suggested that cattle have special cultural significance in the Beni region and households followed much more heuristic accumulation rules that are reflected in the design of SimPachamama.

3. The Model

In this section we systematically describe the model's variables, agents, structure, and specific decision rules following the ODD+D (Overview, Design Concepts, and Details + Human Decision Making) protocol outlined in Muller et al. (2013) as a common, systematic way to describe simulation models to make them more easily comparable. Specifically, first we outline the model's state-space variables and scales, provide an overview of the simulation process and describe the set of decisions taken by each of the three modules. We then outline some general design concepts and describe in detail the specific algorithms and decision rules utilized in each submodel. At the end of the section we discuss issues of model validation.

3.1 State variables and scales

Agents represent farm households, with the maximum number of initial farms equal to 100. The user can define initial population density to be 50, 70, or 100, with lower density allowing more space for community expansion. The maximum number of total farm households in the simulation is 162. State variables that are fixed (exogenous) and common across farm households include the proportion of agricultural land under fallow, the cattle reproduction rate, cattle stocking rate, the urban wage in the city, and the price of agricultural outputs. State variables that are fixed (exogenous) and heterogeneous across farm households include initial plot size, initial land use(forest, cleared land, pasture, fallow), initial cattle herd size, household size, household age, and initial household wealth. Land use patterns, cattle herd, household labour supply and household wealth evolve endogenously. State variables that change endogenously within the model as a result of farm household and Mayor decisions include the rural wage, the Mayor's budget, and the community migration rate. Community-wide state variables that are under the control of the Mayor include the number of non-agricultural jobs ('Green Jobs'), the level of public investment, the level of the deforestation tax, the level of conservation payments, and whether or not international REDD payments are offered.

3.2 Process overview and scheduling

The spatial resolution of the model comprises an area of approximately 330 square kilometres, or 33,000 hectares, with a potential maximum of 162 individual plots arrayed along a road approximately 20 kilometres long, where the initial distribution of plot size reflects the actual observed distribution from the household survey, with all new plots being allocated 50 hectares each, in correspondence with the Bolivian government's settlement policies. This was designed to resemble a typical Bolivian village in the Beni River region (see section 2.2).

The temporal resolution of the entire simulation spans a period of 20 years, with the full series of farm household decisions taking place within each year and the shell module taking the outcomes of these decisions and combining them with the annual choices of the Mayor to calculate the new state-space (available land, size of the cattle herd, rural wage, availability of off-farm jobs) that farm households will face in the next year.

The order of decision making within each of the three sub-components in the model is described below. As decisions made in one module may affect decisions in the other modules, the entire process for a single 'year' involves an interwoven sequence that is depicted by a schematic graphic in Figure 3.

FIGURE 3 HERE

3.2.1 Farm Household Component: Farm Households make a combination of utility-maximization[3] and heuristic accumulation decisions that determine land use and labour market outcomes.

(1) At the start of each period (year) farm households decide the optimal amount of land to cultivate (from land already cultivated) as well as additional land to clear (deforest) for agriculture, given that the costs for cultivating deforested land must include the costs of deforestation. A certain proportion of land must be left fallow in each period. If the optimal amount of land for agriculture is less than the amount already under cultivation, or if deforestation costs are prohibitively high, no deforestation occurs. However if the optimal amount of agricultural land desired by the household is greater than the amount existing cleared land then deforestation will occur as long as the additional benefit is greater than the additional costs associated with clearing. Given the off-farm wage and the household's value of leisure, households choose the required labour supply for cultivation and/or clearing. This includes the possibility to hire in labour at the prevailing agricultural market wage.

(2) Households then compare profits from cultivating newly-cleared land to that available from conservation payments to decide whether it is instead more profitable to set aside land for conservation rather than to deforest.

(3) Households then decide how much land is required for pasture for cattle. As households follow a heuristic accumulation rule for cattle (see section 3.41), they observe the size of their herd, the cattle stocking rate, and the costs of 'harvesting' (selling) cattle, and decide how much land to allocate to pasture for cattle. If they have achieved a profit-maximizing optimal herd size then they sell any excess cattle. If they have not yet reached the optimal herd size, the farm household compares the benefits of expanding the herd to the costs of deforestation for additional cattle pasture (e.g. due to a deforestation tax). The maximum herd size is reached either when it is no longer profitable to clear more land to expand the herd or if the household has exhausted all the land available in its plot. Then any new cattle produced by the herd (reproduction) are sold by the household.

[3] The model assumes that farm households always respond rationally, with full information on prices. Farm households are assumed always to comply with any tax or payment contract. In general, regardless of policy faced, households are assumed always to choose the option which optimises household utility.

(4) After taking into account the possibility of conservation payments and the need for pasture for future cattle herd growth, households decide whether or not to change the area of forest under conservation in order to maximize utility. This decision affects the amount of available land the farm household has at their disposal the following year.

3.2.2 Policy-maker ('Mayor') Component: The policy-maker (Mayor) module is operated by the model user, with the objective to effectively balance household well-being (including community level inequality) and environmental sustainability as reflected in the quintile measures of deforestation and well-being and the community wide 'Score' calculated by the shell module.

The Mayor observes the quintile well-being and deforestation plots as well as her budget. A choice of additional state variables including the daily wage, the total cattle herd and the population growth rate may also be observed, as well as the community Score calculated by the shell module. In turn the Mayor may decide to adjust the level of each of five possible policy levers (described further in section 3.4.2):

1. Public Investment (in education, health & infrastructure)
2. Investment in local, non-agricultural jobs ('Green Jobs')
3. Deforestation Tax (negative incentive)
4. Conservation Payments (positive incentive)
5. International Incentives for reduced emissions from deforestation and degradation (REDD, per ton of avoided carbon dioxide emissions from deforestation)

3.2.3 Shell Component: The shell module will register decisions made by farm households and any changes made by the policy-maker (Mayor) module during the year to calculate outcomes and new state-space for the following year.

Specifically, as explained in more detail below in section 3.43, the shell module:

1. Determines the agricultural wage rate for the next year.
2. Determines net migration that determines population numbers in the next year.
3. Adds population via natural population growth, which is assumed to increase by 2% per year.
4. Increases the size of the cattle herd of each farm-household for the next year based on the natural cattle reproduction rate.
5. Calculates community-wide measures of household well-being and deforestation used to calculate a community 'Score' for that year.

3.3 Design Concepts

3.3.1 Objectives

Farm households make land use and labour supply decisions to maximize utility as a function of consumption and leisure, and follow heuristic wealth (cattle) accumulation rules subject to resource constraints. The policy-maker (Mayor) user adjusts policy levers; the objective depends on the researcher's aim. Normally the objective would be to maximize the overall community well-being, as measured by a multidimensional utility function that takes into account both the level and the distribution of economic wealth, and environmental sustainability as measured by the extent of deforestation. However, a user might decide to try to maximize economic welfare (for example to gauge the environmental impact), to minimize deforestation, or even to maximize the Mayor's budget (for example to simulate a greedy or corrupt government). With five policy levers and 20 years the number of possible policy scenarios is essentially infinite; in section 4 we explore several of these many alternatives.

3.3.2 Agent-Agent and Agent-Environment interaction

The households interact indirectly via changing wages as the labour market clears; labour demand and supply decisions of one household will affect the rural wage in the next year, which in turn will affect other household's labour and land use decisions. In addition, to the extent that the Mayor reacts to changes in aggregate well-being and land use with new policies, households' state space will be affected by other households' decisions.

The model assumes that perfect information of policy impacts is received by the Mayor on an annual basis. In reality there are costly informational requirements that may not be met in poor, rural communities, so this ability to respond instantaneously with policy adjustment overlooks the potential for policy inertia and could provide an interesting extension in the future.

3.3.3 Initialisation and Input

The model is initialised using starting values for each household derived from our household survey for family size, family wealth, family tenure (years on plot), farm plot size, farm land use (forest, cleared land, pasture, fallow), and cattle herd size. Values for global state variables cattle stocking rate and agricultural wage were adopted directly from the household survey as well.

3.4 Submodels

3.4.1 Farm Household Decision Module

The farm household model is described more formally in Appendix 1. Farm households are heterogeneous in their initial endowment of land, cattle, and family size. Total household time (T) is divided between on-farm labour (L), local agricultural wage labour (L^w, where w is the wage rate), off-farm non-agricultural labour (L^{OFF}), and leisure (l). On-farm labour is in turn divided between labour cultivating previously cleared land (L^f) and labour spent clearing (deforesting) and cultivating new land (L^D).

Off-farm labour may be constrained to some level so that $L^w<E$, where E is an upper bound that may be below the optimal level of L^w. In other words, there may be some involuntary unemployment with respect to off-farm labour. We assume all households value both consumption and leisure, and that these can be mapped to a welfare function $U(C,l)=C^{\alpha}l^{\beta}$. However household types differ by the internal and external constraints that they face.

All households have an initial allocation of cleared land, H_{t-1}. This is a proportion of their overall land endowment, and they can clear more land if they choose. By supplying labour to work their land, or renting labour from the local market, they can produce agricultural output, which is translated into consumption at a given rate, p (the price of agricultural output). Households can also work for wages on other farms (at wage rate w), which also generates income that translates into consumption, or they can enjoy leisure, which also brings them well-being. The values of α and β (set to 0.4 and 0.6 respectively) reflect the substitutability of consumption and leisure. Diminishing marginal returns to consumption and leisure are deployed as working assumptions; allocate too much time to consumption-generating labour and the relative marginal well-being from a time unit of leisure will increase until the household maximising reallocates time from labour to leisure.

Given their total household time budget, the wage at which households can earn in the off-farm labour market, w, the limit of off-farm labour they may supply (E), and the production function that maps their labour input and land use to output, households choose how much land to cultivate, how much new land to clear, how much labour to supply to off-farm activities and how much leisure time to enjoy in order to maximise their welfare function: $U(C,l)$.

On the production side, we specify a parsimonious production function for cultivated land that approximates the Bolivian case for smallholders in the area studied. In particular, we assume a linear production function in which labour and land are required in fixed proportion to produce output. However, diminishing productivity of labour and land is captured by a labour requirement that increases with the distance of land from the road. This could be interpreted as a travel cost associated with working far from the road. In addition to the travel cost of distance, the labour required for cultivating cleared land is different from the labour required for clearing (deforesting) and cultivating new land. Thus we have a linear, fixed proportion technology that varies with distance and discontinuously with type of land under production. Figure 4 illustrates the marginal cost for labour as a function of land cultivated.

FIGURE 4 HERE

We assume that each household's agricultural crop land is of a fixed width of 200 metres. This reflects the way in which plots are organised along the roadside in Bolivia and also approximates the arrangement of farming more generally. With the width of the plot fixed, the area of land, H, is also a metric for distance from the roadside. Figure 4 shows how the marginal cost of labour varies with the area cultivated. The endowment of previously cleared land is given by H_{t-1}. The marginal cost of labour on this land is given by ($1+q$) and the total cost of cultivating this land is given by the blue area. If more land is cultivated then deforestation is required, and the marginal cost of labour on this land differs to reflect this: ($1+q+s$), where q captures travel costs of distance and s captures the differential labour required for cultivating new land that must be cleared first. Figure 4 also shows the case where the maximising level of cultivation is given by H^*. In this case, deforestation is required at higher marginal cost: $s > 0$. Local interviews around Rurrenabaque and San Buenaventura on the Beni river indicated that common practice was to exchange forest clearing services for the wood extracted, suggesting that in their case it is likely that s is about zero. Thus, we assume $s=0$, although this parameter can be adjusted for other settings.

Given this discontinuous cost structure, household optimisation proceeds in two steps. First households optimise over their converted land endowment; and second, households make a deforestation decision. The first step can be thought of as a constrained optimisation problem, with the converted land endowment as the constraint. The second step is only considered if the first stage solves as a corner solution (e.g. the household chooses to allocate all of its cleared land to agriculture) and the shadow price of land is positive (e.g. the marginal return of an additional unit of land, if they had it, would be positive). It is therefore necessary, but not sufficient for deforestation to take place in the second stage. If the shadow price is sufficiently high to overcome the discontinuity in cost driven by $s > 0$, then deforestation will occur. If $s < 0$, then deforestation is more likely to occur in step 2 if there is a corner solution due to lower marginal costs.

In addition to using land for crops, clearing pasture for cattle is a major driver of deforestation in the Amazon Basin (e.g. Andrade de Sa et al., 2013) and is an important component of land use around the Beni river area. Cattle also have the unique property that, unlike crops, they reproduce; diminishing returns to land are modelled by assuming that livestock follow a standard logistic growth function and the marginal cost of harvesting are assumed to be increasing, reflecting some diminishing returns to extensive production. This could be motivated by monitoring costs, costs of disease, etc., akin to the costs of distance in the agricultural model. Farm households choose a profit-maximizing optimal cattle herd size (see Appendix 2) and accumulate cattle each year as long as the costs of deforestation for pasture expansion do not exceed the benefits.

3.4.2 Policy-maker (Mayor) decision module

The Mayor's module allows for 'real time' policy adjustments to be made by the user. The shell module provides the mayor with a host of information about the current state-space, including the average well-being of the households (explained in detail in section 3.4.3), the extent of deforestation, the number of cattle, the wage level, and the local government's (Mayor's) budget. Based on this information the Mayor can make adjustments to the following policy levers: Public Investment; Investment in local, non-agricultural jobs (Green Jobs); Deforestation Tax; Conservation Payments; International Incentives for reduced emissions from deforestation and degradation.

Public Investment combines investment in education, health and public infrastructure. Such investments tend to increase human well-being but are also costly. The default value of *Public Investment* is set at USD 15,000 per year, which is approximately the amount the community receives in transfers from the central government every year. In Bolivia, this money comes mainly from the Direct Tax on the extraction of oil and gas and amounts to approximately USD 50 per person depending on the price of oil. As the local government spends this down or brings in additional funds, this budget may increase or decrease.

The second type of policy intervention is to provide alternative off-farm employment opportunities which cause less deforestation and at the same time higher incomes. This not only has favourable direct effects on the people who are employed, but by reducing the supply of agricultural labor these initiatives also lead to increases in agricultural wages, which in turn tends to both reduce economic inequality as well as raise the costs of agriculture and deforestation. We dub these *Green Jobs* policies as they have a series of attractive effects, but they are also extremely expensive. For example, if the local government wants to stimulate jobs in the tourism sector, it has to invest in good tourism facilities, such as roads, airports, water, sanitation, communication, etc. We assume the cost of one Green Job at USD 6,000, about half the estimated country-wide average investment needed to create a job in Bolivia (Muriel and Jemio, 2010).

The *Deforestation Tax*, between 0 and USD 500 per hectare, will directly affect the decision to deforest. If very high, farmers will find it more profitable to cultivate already cleared land instead of deforesting new areas, and cattle ranchers will choose to sell more of their cattle instead of letting the stock increase every year. At the same time, the Tax reduces household net incomes and thus their level of well-being. Although the Bolivian government has recently implemented such a tax, the revenues go directly to the central government. Local communities do not currently perceive any benefits from this tax. Instead, it is viewed as a drain on community revenues, reducing both incomes and jobs. Even though such a decentralized Tax is hypothetical for the case of Bolivia, it is plausible given recent, global trends to decentralize natural resource management (see Larson and Soto, 2008). In focusing on taxing deforestation, we abstract from taxation elsewhere in our economy, e.g. on consumption, that may also influence land use.

The last local policy lever, *Conservation Payments*, represents a scheme where households are offered a financial incentive for any land that they promise to keep forested for at least 20 years. The scheme is similar to SocioBosque in Ecuador and COMSERBO in Pando, Bolivia, with annual payments varying from 0 to USD 100 per hectare. When offered the option of participating in such a scheme, each household will calculate how much land it is optimal for them to dedicate to conservation, and how much it should make available for its agricultural needs. In addition, while all policies can be changed at any time during the 20-year simulation period, we assume that if the Payment is changed, households who have already signed a Payment contract are liberated and free to re-optimise their decision under the new conditions.

Finally, in addition to the four local policies, we include the possibility of accepting an *International Incentive* for reducing emissions from deforestation and degradation (REDD), e.g. financed through the voluntary carbon market, at the community level.[4] When this option is active the community will receive a reward for every hectare of reduced deforestation, with a default price of USD 5,000 per hectare. This corresponds to USD 10 per ton of avoided CO_2 emissions from deforestation, and can be adjusted in the model.[5] The 'Reduction' is calculated as the difference from the 'business-as-usual' scenario obtained by letting the model run for 20 years with only default Public Investment.

[4] Bluffstone et al. (2013) discuss the practicalities of community-controlled forests participating in REDD+.
[5] Bolivian forests have the potential to release, on average, about 500 tons of CO_2 per ha, if burned.

3.4.3 Shell Module

Each year the Shell module evaluates human well-being and deforestation per capita for each quintile of well-being in the population (itself a function of wealth, leisure, ecosystem services and public infrastructure). The community receives five scores (as illustrated in Figure 5) corresponding to the average well-being and deforestation per capita of each quintile. These five quintile scores sum to the community 'Score' for a given year.

Calculating deforestation per capita is straightforward. To calculate the human well-being of each household the shell module evaluates a five-argument Cobb-Douglas multidimensional well-being function in the spirit of Schreinemachers and Berger (2011):

(1) $$W(c, l, x, ES, PI) = c^{\alpha} l^{\beta} s^{\gamma} ES^{\delta} PI^{\varepsilon}$$

Where:

c = private consumption per capita (average consumption within the family, measured in tons of rice equivalents).

l = private leisure per capita (average leisure within the family, measured as a fraction of total time available in a year)

x = private cattle stock per capita (average number of cattle per person within the family)

ES = ecosystem services (total forest area in community measured in square kilometers)

PI = public infrastructure (stock of public infrastructure measured in millions of USD).

Well-being is measured in Happy Life Years (HLY) scaled between 20 and 80 (NEF 2009). The parameters α, β, γ, δ and ε are set to reflect how much time households would typically dedicate to/benefit from each component in an average 24-hour-day. For example, people generally often demand least 10 hours of leisure per day, so β has been set to 0.4. They would dedicate about a third of the day to production for consumption so α has been set to 0.3. Since cattle constitute their main savings vehicle, and people would like to save about 5% of their potential income (corresponding to about 10% of realized income), we have set γ to 0.05. Ecosystem services from the forest surrounding the community provide services that we assess to be roughly equal to a couple of hours of work per day, so δ is set to 0.1. The same kind of logic holds for public infrastructure, like roads, schools, health clinics, etc., and we have set ε to 0.15.

For each quintile, average well-being (calculated from all households in the quintile using equation (1)), and average deforestation per capita are plotted by the Shell module in 'well-being – deforestation' space, which in turn is divided into four ringed zones. Each zone corresponds to a score indicating how well the two objectives have been achieved. The approach is illustrated below in Figure 5, with each of the four rings earning a score of 25, 10, 5 and 0, respectively. The community Score is then the sum of the individual quintile scores (in the example in Figure 5, for example, the score would be 20) . A high Score would therefore represent a situation in which most if not all quintiles are to be found in the top-left zones; lower Scores, on the other hand, are suggestive of trade-offs at least for one or more quintiles and indeed possible inequalities emerging in the community.

FIGURE 5 HERE

In addition to calculating and evaluating economic, social and environmental progress, the shell module updates several features of the state space in which the households will make their decisions in the following year. First, the shell module determines the agricultural wage rate for the next year. Labour market clearing occurs by taking into account all available jobs (including labour required for agriculture as decided by the farm households), if there remains unemployment then wages remain at the minimum level. If there are more jobs than there are workers, then the wage increments upwards towards the maximum wage. The increment is the larger the larger is the labour demand gap. The new wage will be the agricultural market wage in the next period.

Secondly, to determine the percentage of in-migration the module compares the current and previous year's community Score and increases the local population by 0.1% for each one point increase in the community well-being score, up to a maximum of 5%., as long as land is available and community well-being is above 25 HLY. The families that arrive are very poor (four persons in each family, zero savings) and are allocated a 50 hectare plot on the next empty spot along the road, along with one cow. They then start farming according to the farm household model.

To determine out-migration the module increases by 0.1 percentage points of the population for every USD 2,000 in Public Investment (which increases education) up to the maximum of 5% per year, while for every non-agricultural job created, out-migration is reduced by one randomly chosen person.

Third, the shell module also adds population via natural population growth, which is assumed to increase by 2% per year, with households adding the requisite number of new members every 20 years to achieve this. As households begin the simulation with varying lengths of residency, this population growth in practice is achieved with some subset of households increasing in size each period. In addition, following the standard of the Bolivian settlement policy in this area (INRA, 2007), each additional new person is allocated 50 hectares of forested land, which is appended to the household plot.

Finally, the shell module increases the size of the cattle herd of each farm-household for the next year based on the natural cattle reproduction rate which is assumed to follow a standard logistic function as:

(2) $$G(x) = \sigma x + \mu x^2$$

where *x* denotes the stock of cattle per hectare, and growth parameters $\sigma > 0$ and $\mu < 0$ where σ is the "intrinsic growth rate," which we set to 0.25, and $-\sigma / \mu$ is the carrying capacity of a hectare of land, which based on field observations and the household survey we set equal to 1.

3.5 Model Validation

The optimising behaviour of our farm households was validated first, by construct, on the basis of well-established theories of the household in development and agricultural economics, e.g. Angelsen (1999). Since our initial parameter values are set to quantitative household data collected in the field we have a perfect initial goodness-of-fit. Further model validation by results was achieved by studying the model in the baseline scenario (see Section 4). Although the results seem sensible, we cannot undertake further analysis due to the fact that the household data are only available as a cross-section; in order to test whether or not the simulated results over time are consistent with observed household behaviour we would need panel data, which are currently unavailable.

The workshops and ethnographic research described in Section 2 helped in validating local land use behaviour and the policy setting. Our assumption of myopic households is based on the observation that households, particularly poorer ones, often had relatively short time horizons, and where there was potentially forward-looking behaviour, notably households' preference to save via the accumulation of cattle, households tended to follow heuristic rules that varied little from year to year. To the extent that our assumption of myopia is an oversimplification, however, we note that it was a necessary one, as optimising both agricultural and cattle decisions dynamically over the runtime of the model, combined with the real-time policy adjustments made by the Mayor, would have been too computationally demanding.

4. Results

Our approach allows for quasi-general equilibrium, quasi-dynamic modelling that is based largely on micro-fundamentals, while also permitting us to explore the implications of highly heterogeneous households and general equilibrium feedback effects. The shell module plays the role of producing the latter effects that would not have been apparent from a simple partial equilibrium analysis of the household, but in a more feasible manner and at much lower computational cost than a true dynamic general equilibrium optimisation model.

An important difference between our hybrid model and more conventional policy analysis tools is that the mayor receives feedback on a range of economic and environmental state-space characteristics from the shell module in real time over the run of the simulation. In response to this feedback, she can adjust any of the policy levers to try to influence community outcomes. As such, our approach more closely approximates real world policy making, although unlike the real world our mayor can experiment by making multiple attempts to influence outcomes. The potential to explore outcomes produced by different combinations and dynamic sequences of policies means that, in theory, there are an almost infinite number of possible combinations and alternative sequences of policies that could be tried. While this precludes the use of Monte-Carlo simulations on random combinations of dynamic policy choices, here we present a number of general results for the policy choices of a mayor whose chief aim is either maximising revenue ('greedy mayor'); maximising well-being (e.g. via Public Investment); reducing deforestation (Conservation Payments); or jointly maximising well-being and reductions in deforestation (via a combination of policies).

We begin by simulating the business-as-usual (baseline) scenario in which the only policy is the default USD 15,000 of Public Investment, funded by lump sum transfer to the mayor from the central government. Since this is the only money entering or leaving the community, it represents a very localised and self-contained economy (the mayor cannot borrow in order to finance policy). The first column of Table 2 (where Deforestation Tax is set to zero) reports the baseline outcomes of deforestation, number of cattle, wage rate, well-being, and the community Score.

TABLE 2 HERE

An important thing to note is that once policies (beyond the baseline USD 15,000 of Public Investment) are implemented, the mayor tends to run out of money very quickly, thus ending the simulation. Consistent with the fiscal reality of most local governments, the Mayor in SimPachamama must raise revenue to fund additional policies, and in the model this may come from two possible sources: a Deforestation Tax and an International Incentives for reducing emissions from deforestation and degradation. While both of these policy levers are expected to affect both well-being and deforestation, they are primarily implemented by the Mayor as a means of reducing deforestation. The results of simulating a local Deforestation Tax can be seen in Table 2.

As the Deforestation Tax rises with each increment of USD 50 per hectare, the amount of deforestation steadily declines, as does the number of cattle, while well-being remains initially stable. The fact that aggregate community well-being doesn't fall at lower levels of Tax reflects the fact that it is mainly paid by a small number of wealthier (larger) cattle ranchers, who need much more cleared land than subsistence farmers. When the revenue generated supports further Public Investment (not shown) it therefore acts as a kind of 'Robin Hood' tax, with the revenues redistributed from the wealthiest to the poor through public spending, hence reducing inequality.

Shown in Table 2, the community Score increases due to reductions in deforestation, and the Mayor is able to stay within her budget constraint for the entire 20-year period. Between USD 300 and USD 400 per hectare, however, there is a sudden sharp drop both in deforestation and well-being. From this relatively high Tax level onwards it is not possible to reduce deforestation any further. A high Tax also drives people out of the community thus resulting in negative annual population growth in some years. The fall in well-being can be explained by the fact that the Mayor is not investing any of the revenues from the Tax in the community (a 'greedy mayor' scenario). In turn, this drop in well-being dominates the fall in deforestation, thus explaining the decline in the Score. In the model, the Tax can, however, be used to finance other policies, which could help build and maintain local support for policy goals as well as allowing greater flexibility in local policy-making.

In Table 3, we set the Tax at the median level of USD 250 per hectare and explore outcomes from policies aimed at increasing well-being (Public Investment and Green Jobs) that occur, yet without the benefit of International Incentives for reducing emissions from deforestation and degradation. Note that all policies are implemented independently from the first year of the simulation and are on top of the annual transfer from the central government of USD 15,000 for Public Investment.

TABLE 3 HERE

The results in Table 3 show that well-being increases with increased Public Investment, which drives higher community Scores. Deforestation and cattle numbers also appear to rise slightly with Public Investment despite the Deforestation Tax. This occurs because of increased in-migration due to the higher level of community well-being. Table 3 also illustrates that at the level of Tax chosen (USD 250 per hectare), the Mayor is limited in the amount by which she can increase Public Investment; USD 50,000 or more is infeasible. Nor can she afford to invest in any Green Jobs. Expensive investments, such as the creation of Green Jobs, can be introduced only as the Mayors' revenues increase. For example, a Green Job policy becomes more of an option if the Mayor elects to receive revenues from International Incentives for reduced deforestation (see below). If funds are only available from the Deforestation Tax, a possible alternative strategy (not shown) is for the mayor to implement a maximum tax on deforestation and save for some years, in order to create a few Green Jobs during the latter years of the simulation run.

Table 4 repeats the exercise presented in Table 3, but now also allows for International Incentives for reduced emissions from deforestation and degradation. International Incentives are provided at the community, not individual, level after land clearing decisions have been made. We set a price of USD 10/tCO_2, corresponding to USD 5,000/ha of avoided deforestation. As a comparison of the results in Tables 3 and 4 makes clear, International Incentives provide a powerful opportunity for local governments to collectively lower deforestation. The complementary combination of International Incentives and a Deforestation Tax greatly increases the Mayor's budget and allows for much greater expansion of social policy than either International Incentives or Deforestation Taxes alone. For example, additional Public Investment is possible and even a few Green Jobs can be introduced.

TABLE 4 HERE

We now consider a scenario in which the Mayor is focused on reducing deforestation, accepting International Incentives and implementing a Conservation Payment financed by a Deforestation Tax. We assume that any excess revenue not spent on Conservation Payments are invested first in Public Investment and finally, if funds remain, on Green Jobs (e.g. we assume a benevolent, rather than greedy, mayor). This policy combination demonstrates that the effects of the different policies are not only non-linear, but that they also interact in complex ways. Figure 6 shows that increasing the size of the Conservation Payment will contribute to further reductions in deforestation, but only if the Tax is low. The result illustrates that very high levels of Deforestation Tax dominate household decision making and result in reduced deforestation regardless of the level of Conservation Payment. In these cases, Conservation Payments have no additional impact and simply act as a fiscal transfer to households. But at lower Deforestation Tax rates, as expected, the Tax is much less effective in reducing deforestation and hence, even relatively low Payments can have an impact on reducing deforestation against the baseline.

FIGURE 6 HERE

Conservation Payments also have an indirect effect on inequality in the simulation. In general, farmers and ranchers in the model calculate how much land they are going to need for the next 20 years and the land they volunteer in exchange for Conservation Payments tends to be that which is the least profitable to cultivate, i.e. to be found farthest away from the road. This therefore implies that the poorest households tend to benefit disproportionately from this scheme, as they will often not have the financial resources to cultivate their entire plot anyway.

As discussed, the Deforestation Tax cannot be too low because otherwise there is insufficient money in the Mayor's budget to finance policies, including the Conservation Payments. For example, if the Tax is USD 100/ha, then the Payment cannot increase to more than USD 30/ha/year without the mayor running out of money. In contrast, with higher Taxes (above USD 350/ha), adding a Payment does little to further reduce deforestation.[6] In line with the results in Table 3, this is because marginal land has already been removed from production due to the Tax and quite a high payment would be required to further reduce deforestation.

Conservation Payments could potentially increase human well-being, as participants are in effect receiving windfall income. The simulations do not confirm this, however. Indeed, Figure 7 shows that for each given level of Tax, the Score decreases with higher Payments. This decline is due to reductions in human well-being, and is particularly steep for lower Tax rates because the Mayor's budget is smaller than at higher rates. Thus, for each dollar spent on Payments is one less dollar allocated to Public Investment or Green Jobs. At higher rates of Tax, this is less of an issue. But given the model parameters, it is only optimal to make Payments if there is money left over, i.e. after allocating Tax revenues to Public Investment and Green Jobs.

FIGURE 7 HERE

In sum, if the Mayor does not implement a Deforestation Tax early on, she will run out of money very soon after implementing one or more of the other policies. Yet even at high Tax levels, it is challenging to stay within budget while simultaneously increasing well-being and reducing deforestation. Introducing the International Incentive for reducing emissions from deforestation and degradation helps the mayor overcome this apparent trade-off between well-being and deforestation even at relatively modest carbon prices. Indeed, if the mayor is successful at halting deforestation, she receives revenues sufficient to spend on policies to improve well-being.

Our results suggest that policies have to be continuously adjusted and fine-tuned in order to obtain the desired outcomes, and that correct sequencing is critical. Revenue must be generated to fund policies that both raise well-being and in turn generate more revenue. This in turn stresses the need for policies that are not only effective in reaching their aims but also efficient in their use of public funds. Although an obvious point, it continues to be neglected in discussions about policy design and implementation in tropical forests. Reduced deforestation, whether induced by Deforestation Taxes, Conservation Payments or International Incentives, provides some positive effects for well-being but by itself does little to improve well-being sufficiently to compensate for lost agricultural output. Thus, spending on Public Investment and Green Jobs is essential to achieve improvements in both environment and development.

[6] The optimal tax is not necessarily the highest tax; a tax of $350/hectare was found to be the optimal tax, both with and without international compensation for reduced deforestation.

5. Discussion and conclusions

Policy interventions designed to simultaneously stem deforestation and reduce poverty in tropical countries entail complex socio-environmental trade-offs. In order to explore these trade-offs we develop a model of land use change and human well-being using a parsimonious representation of agricultural and economic decisions that emerges from both quantitative and qualitative research on the local socio-economic context and culture of the Beni river region in lowland Bolivia. While our hybrid, optimising-heterogeneous agent model ('SimPachamama') is calibrated to the initial conditions of these smallholders, the optimisation problems solved by the agents across a number of dimensions are broadly generalisable. In particular, heterogeneous households endogenously choose how much land to cultivate, how large a cattle herd to maintain, and whether to expand at the extensive margin by deforesting. The optimisation problem of households takes into account wage differentials and the availability of local non-agricultural jobs to determine how much labour to rent out or rent in agricultural labour markets, and how much labour to supply outside of farming activities.

The Mayor (model user) makes policy choices in 'real time' subject to her budget running out of money, which in turn impacts households' opportunities; the net effect of these decisions is transmitted to the next period through stock, wage and price adjustments via the shell module. Continuous policy adjustments by the Mayor alter the trajectory across both socio-economic and environmental outcomes. Thus an important difference between SimPachamama and other commonly used socio-agricultural simulations is that our approach allows the user to experiment with alternative policy bundles and sequences, observing the consequences of policy changes in 'real time.' While the instantaneous, perfect information of the Mayor may be unrealistic for modelling policy inertia and other real world phenomena, it does allow users in this role over repeated simulation runs to gain an understanding of the potential trade-offs and complementarities of policies aimed at improving economic outcomes and reducing environmental harm. Furthermore, the graphically sophisticated game-like interface of SimPachamama makes the simulation accessible to a wide range of users, including not only researchers and students but also policy makers and local stakeholders, making the model a useful tool for encouraging local participatory engagement and student learning.

In addition to its pedagogical features, the potential to explore multiple outcomes produced by different combinations and dynamic sequences of policies also makes SimPachamama a powerful resource for researchers, with an almost infinite number of possible combinations and alternative sequences of policies that could be explored. Furthermore, the open-source nature of the code allows more advanced users to change other features currently fixed in the simulation (for example, it would be possible to explore the implications of a change in the government policy of allocating 50 hectares to new households, or of a change in agricultural technology).

In this paper, we report a number of interesting and consistent predictions and implications related to policy bundling and sequencing that have emerged from much experimentation in choosing and adjusting policy levers throughout multiple runs of the 20-year simulation. A key finding is that in the absence of outside finance there are significant and virtually unavoidable trade-offs between human well-being and reduced deforestation. Deforestation Taxes can reduce land clearing and raise critical revenue for local public policies but only if the revenue from the Tax remains in local hands and is used appropriately; otherwise, Taxes on deforestation have the potential to reduce well-being.

Our results reinforce the idea that sequencing of policies is critical for long-run successful outcomes, and policies can have unexpected nonlinear effects both independently and in combination. Policy complementarities emerge, such as that between Conservation Payments and Deforestation Taxes, since these policies have different effects on the Mayor's budget and thus indirectly on household decisions and well-being. International REDD incentives can help relax constraints on public funding, reducing the local tax burden and bringing reductions in deforestation forward to the extent that a surplus need not be generated in the first few years.

In conclusion, our model has proven to be a useful tool for encouraging local participatory engagement and exploring a wide range of policy choices and trade-offs. We have made SimPachamama publicly available and open-source, so parameters can be adjusted or re-calibrated to other settings. In addition the hybrid modular structure allows for the potential to add new elements into the model at relatively low cost; for example, in its current form we have not yet introduced any explicitly spatial interactions, but through the shell module this is a straightforward extension of the model.

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Appendices

Appendix 1: The Household Model

For a separable household the problem is simple profit maximisation. With output price, *p,* normalised to 1, and labour receiving the market wage *w*, the problem can be described as follows. Households at time *t* have some already converted land from the previous period: $H_{t-1} \geq 0$. Cultivation in excess of this requires deforestation to take place. Labour and land are assumed to be the only inputs to production. Labour used on previously cultivated land is given by:

$$L^f = L^{fo} + L^{fh}$$

Labour used on deforested land is given by:

$$L^D = L^{Do} + L^{Dh}$$

Labour is applied to converted and unconverted land in a fixed relationship depending on distance from the road. Labour can be provided from the households own family $\left(L^{fo}\right)$ or hired $\left(L^{fh}\right)$. Note that if L^{fo*} is greater than the constraint H_{t-1} allows, then it is possible that $L^{fh} = 0$, and hired labour is then only used for deforestation. Production, *X*, is linear in already converted land used, H , and deforested land, *D*, and a technology parameter *A:*

$$X = AH + AD$$

Profit is therefore written as follows:

$$\Pi = p(AH + AD) - w\left(L^f + L^D\right),$$

Labour and land have a fixed relationship such that the amount of labour required for each additional hectare is given by:

$$\frac{\partial L^f}{\partial H} = (1+q)H$$

Given this, an expression for *H* as a function of labour can be obtained via integration. With the width of the plot fixed, *H* is a measure of distance and so the parameter *q* can be interpreted as a distance cost of labour (see also Angelson, 1999). As discussed in the main text, this distance cost changes when deforestation is privately optimal and becomes *q + s*. Profit maximisation proceeds in two steps:

Step 1: solve for H^*

$$\max_{L^f} \Pi$$

subject to the constraint that labour used on converted land is limited by the amount of land converted in the previous period (H_{t-1}):

$$H_{t-1} \geq \left(\frac{2L^f}{1+q}\right)^{\frac{1}{2}}$$

With the functional forms given the first order conditions obtain L^{f*} :

$$L^{f*} = \left(\frac{(1+q)w}{Ap}\right)^2 \frac{(1+q)}{2}$$

The split of L^f between L^{fo} and L^{fh} is determined by the well-being maximisation problem and the choice of 'leisure'. The first order conditions of this problem obtain that the MRS of labour and consumption (the shadow price of labour) should equal the wage rate (given that the price of output =1) that is $l^* : U_l / U_c = w$. If the solution in step 1 is interior then the household stops there. If the land constraint is binding the household moves to step 2. Otherwise it is easy to show that with preferences given by $u(c,l) = c^{\alpha} l^{\beta}$ the solutions for l and c become:

$$l^* = \frac{\beta\left(\frac{(pA)^2}{2(1+q)w} + wT\right)}{(\alpha+\beta)w}, \quad c^* = \frac{\alpha\left(\frac{(pA)^2}{2(1+q)w} + wT\right)}{(\alpha+\beta)p},$$

Where $\Pi^* = \frac{(pA)^2}{2(1+q)w}$ is the profit function.

Step 2:

If $\frac{A}{(1+q)}\left(\frac{2L^f}{1+q}\right)^{-\frac{1}{2}} - w > 0$: move to step 2 and consider deforestation. This means that $L^{f0} = L^f = L^f_{t-1}$, i.e. the labour associated with the constraint on H_{t-1}. If not then the solutions become:

$$l^* = \frac{\beta(\Pi^*(p,w) + wT)}{(\alpha+\beta)w}, \qquad c^* = \frac{\alpha(\Pi^*(p,w) + wT)}{(\alpha+\beta)p}$$

$\Pi^*(p,w,)$ is once again the profit function. Given the leisure decision, we can now define the labour allocations using the constraints.

Households are endowed with overall time T . Time is divided between on farm work, L^{fo}, 'leisure', l, and off-farm labour L^m. The constraint can be written: $T = L^{fo} + L^m + l.$ L^{fo*}

can be calculated as the residual:

$$L^{fo*} = T - l - L^m$$

and:

$$L^{f*} = T - l - L^m + L^{fh*}$$

or more intuitively:

$$T - L^{f*} - l^* = L^m - L^{fh*}$$

where the right hand side is the net off-farm labour supply (the difference between what is rented in and what is rented out).

Step 2: The Deforestation Decision

If it turns out that there is no internal solution $(m > 0)$, the deforestation decision is evaluated as in previous models. Where L^f_{t-1} is the labour requirement for production on the previously cultivated land H_{t-1}, and since $\frac{\partial L^D}{\partial D} = \frac{1}{2}(1+q+s)D + (1+q)H_{t-1}$ the first order conditions for an interior solution are:

$$D^* : \frac{\partial \Pi}{\partial L^D} = 0$$

Which leads to D^*:

$$D^* = \frac{\frac{Ap}{w} - (1+q)H_{t-1}}{(1+q+s)}$$

These are the analytical solutions. This defines the total amount of labour applied to land, L as follows:

$$\begin{aligned} L^* &= L^{f*} + L^{D*} \\ &= L^f_{t-1} + L^{D*} \\ &= L^o + L^h \end{aligned}$$

The last line shows that labour is split between own and hired labour. It is possible to identify each of these allocations once the well-being maximisation problem has solved for the leisure decision.

Appendix 2: The Cattle Model

Specifically, assume the instantaneous stock of cattle is given by $X(t)$, the 'harvest' (the amount of cattle sold) is given by $R(t)$, which can be sold at price p_C. Variable costs of selling off cattle are given by $c(R, X) = cRX$, and are determined by the size of the herd X as well as the number of cattle that are sold, R. The cost parameter is c.

Step 1: The intensive decision

In the first step the technological decision is conditioned on the biological/agronomic constraints of land and cattle. We assume that households are separable profit maximisers who understand the intertemporal nature of the stocking decision and undertake a dynamic optimisation.

The intensive decision is a per-hectare decision. Diminishing returns to land are modelled by assuming that livestock follow a standard logistic growth function of the form:

$$G(x) = \sigma x + \mu x^2,$$

Where x is cattle per hectacre, with growth parameters $\sigma > 0$ and $\mu < 0$ where σ is the "intrinsic growth rate" and $-\sigma / \mu$ is the carrying capacity of a hectare of land. This represents the production function of livestock. Different technologies would be reflected by different values for these growth parameters, leading to different reproductive growth and carrying capacities.

The dynamic profit maximisation (where r is harvest per hectacre) problem for the household/farm is therefore:

$$\max_r \int_0^T p_c r(t) - cr(t)X(t)\exp(-\delta t)dt,$$

subject to constraint on the initial stock and the livestock growth dynamics:

$$x(0) = x_0$$
$$\dot{x} = G(x) - r$$

The current value Hamiltonian of this dynamic problem:

$$\Lambda(r; x) = p_c r - crx + \lambda(\sigma x + \mu x^2 - r)$$

Appendix 3b below shows that the steady state solution to this problem for R and X is given by the positive root of the quadratic $ax + bx^2 + d = 0$:

$$x^* = \frac{a \pm \sqrt{a^2 - 4bd}}{2b}$$

And:

$$r^* = \sigma x^* + \mu x^{*2}$$

Where $\alpha = (p_c 2\mu + cr - 2\sigma)$, $b = -3\mu$ and $d = p_c(\sigma - r)$, are collections of the parameters.

Step 2: The extensive decision

The intensive decision determines the cattle per hectare, and the harvest rate. What remains is the extensive decision, that is, how much land (H) is used in the cattle operation. Step 2 of the model proceeds as follows.

For simplicity we assume linear relationships between land (H), other variable costs (C_v) and livestock total harvest (R) of the form: $H = \theta X$, $C_v = \gamma X$, and $R = \phi C_v$, where C_v are variable input requirements. This assumption means that the problem effectively involves one decision variable. The values of θ, γ and ϕ can be determined by the solution to step 1: the intensive problem. E.g. the intensity of cattle (cattle per hectare) $x^* = q^{-1}$ which was determined in step 1.

Profit is derived from the revenue from harvest $(p_C R)$ minus the costs of variable inputs: land (H), other variable costs (C_v)[7], and fixed costs, F_C. The marginal cost of harvesting are assumed to be increasing, reflecting some diminishing returns to extensive production. This could be motivated by monitoring costs, costs of disease, etc., akin to the costs of distance in the agricultural model. We assume a cost curve for harvesting of the form $c(R) = cR^k$ where $k > 1$, and c is a constant, ensuring that $c'(.) > 0, c''(.) > 0$. Given the linear relationships above, the instantaneous profit maximisation problem can be written as:[8]

$$\max_H \pi = p_c \frac{\phi\gamma}{\theta} H - c\left(\frac{\phi\gamma}{\theta} H\right)^k + p_H(\bar{H} - H) - p_v \frac{\gamma}{\theta} H - F_c$$

where the price p_H reflects the opportunity cost of land. The general solution to this problem is:

$$H^* = \frac{\theta}{\phi\gamma}\left(\frac{p_c - p_v\phi - p_H \frac{\phi\gamma}{\theta}}{kc}\right)^{\frac{1}{k-1}}$$

$$R^* = \frac{\phi\gamma}{\theta} H^*$$

[7] These could include costs such as feed.

[8] Note: $R = \frac{\phi\gamma}{\theta} H$, so as cattle per hectare increases (θ^{-1}) , so does the harvest.

This shows that H^* is inversely related to: i) the cattle per hectare (θ^{-1}) ; ii) the marginal cost parameters, c and k; iii) the harvest per unit of variable inputs (γ); iv) other variable costs per head of cattle; and lastly, v) H^* is negatively related to p_H, and this relationship is stronger if the cattle intensity is higher. The costs of variable inputs (p_v) and the price of land (p_H) affect land in slightly different ways. The effects on land translate linearly into aggregate harvest (R), input requirements (I_v) and the total stock of cattle (X). The resource constraints associated with the dynamic intensity/harvest decision, when land is constrained, are embodied in the parameters q, g, and ϕ .

Solution to the Livestock Problem Step 1

The first order necessary conditions for an optimum are:

$$R^*: \; p_c - cX - \lambda = 0$$
$$\lambda^*: -\frac{\partial H}{\partial X} = \dot{\lambda} - r\lambda = cR - \lambda(\alpha + 2\beta X)$$

The general solution becomes:

$$\frac{\dot{\lambda}}{\lambda} = r - (\sigma + 2\mu X) + \frac{cR}{\lambda}$$
$$= r - (\sigma + 2\mu X) + \frac{cR}{p_c - cX}$$

In the steady state where $\dot{\lambda} = 0$ and $\dot{X} = 0$, the steady state stock and harvest rate are determined by the following equations. In this is a quadratic equation of the following form:

$$aX + bX^2 + d = 0$$

where:

$$a = (p_c 2\mu + cr - 2\sigma)$$
$$b = -3\mu$$
$$d = p_c(\sigma - r)$$

The solution is then:

$$X^* = \frac{a \pm \sqrt{a^2 - 4bd}}{2b}$$

The steady state solution for R^* is then simply:

$$R^* = \sigma X^* + \mu X^{*2}$$

Solution to Livestock Problem Step 2

The maximisation problem is:

$$\max_{H} \pi = p_c \frac{\varphi\gamma}{\theta} H - c\left(\frac{\varphi\gamma}{\theta} H\right)^k + p_H(\bar{H} - H) - p_v \frac{\gamma}{\theta} H - F_c$$

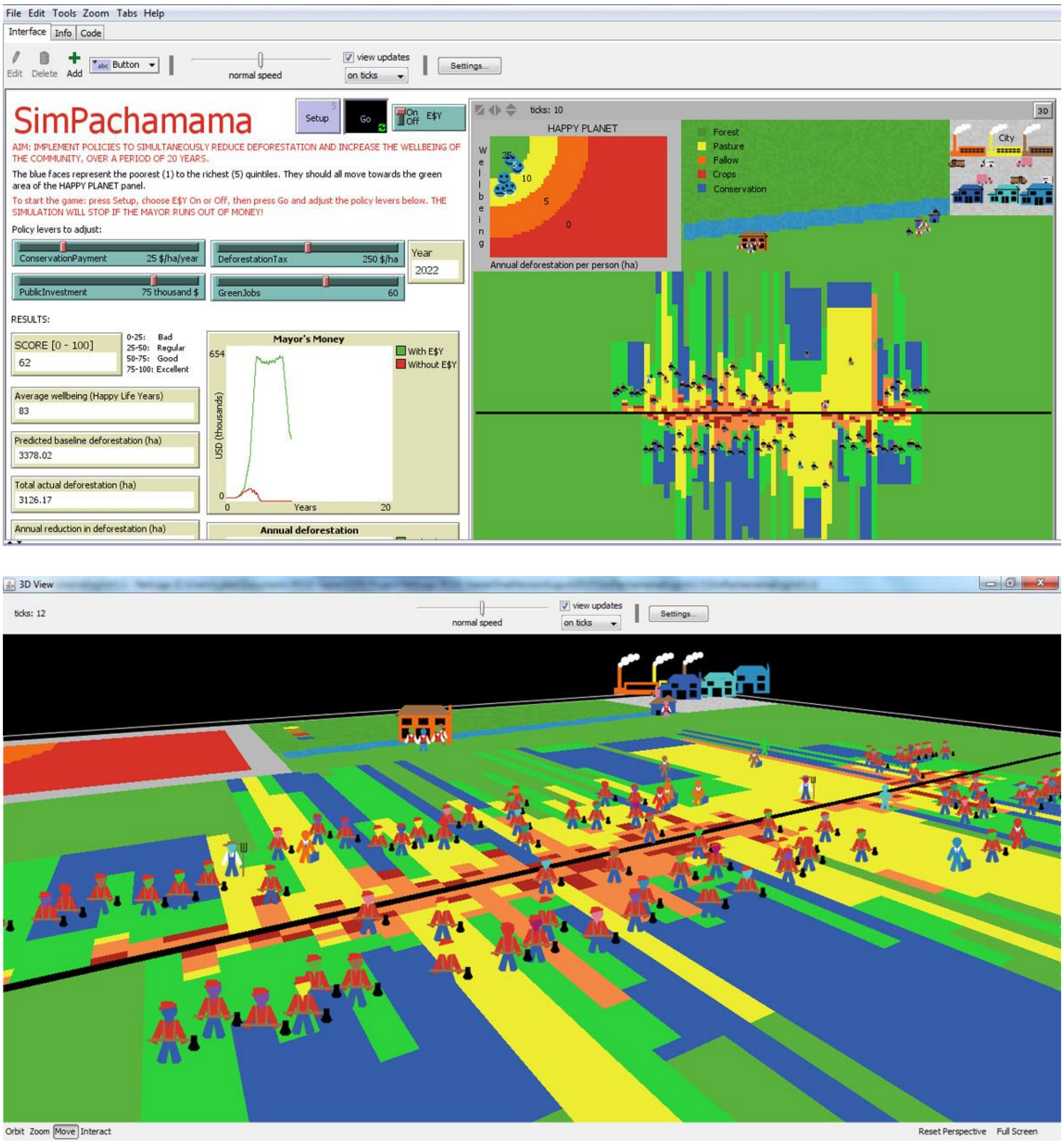
The Solution is:

$$H^* = p_c \frac{\varphi\gamma}{\theta} - \frac{\varphi\gamma}{\theta} kc \left(\frac{\varphi\gamma}{\theta} H\right)^{k-1} - \frac{p_v\gamma}{\theta} = 0$$

From which it is straightforward to derive the remaining solutions.

Tables and Figures

Figure 1: 2D and 3D screen shot from the model, called ‘SimPachamama’



Note:

Download SimPachamama at: http://www.inesad.edu.bo/simpachamama/download/

Figure 2: Google Maps satellite view of typical land use pattern near San Buenaventura, Bolivia

Figure 3: Graphic schematic depicting the one period ('year') sequence of interwoven modular decisions

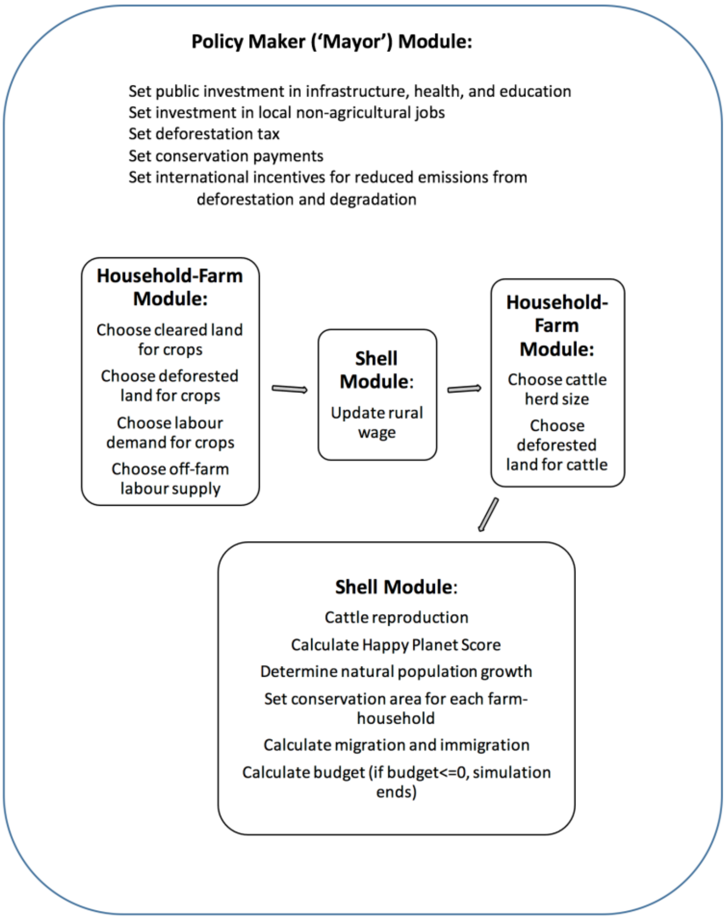


Figure 4. The marginal cost of labour as a function of distance from the road

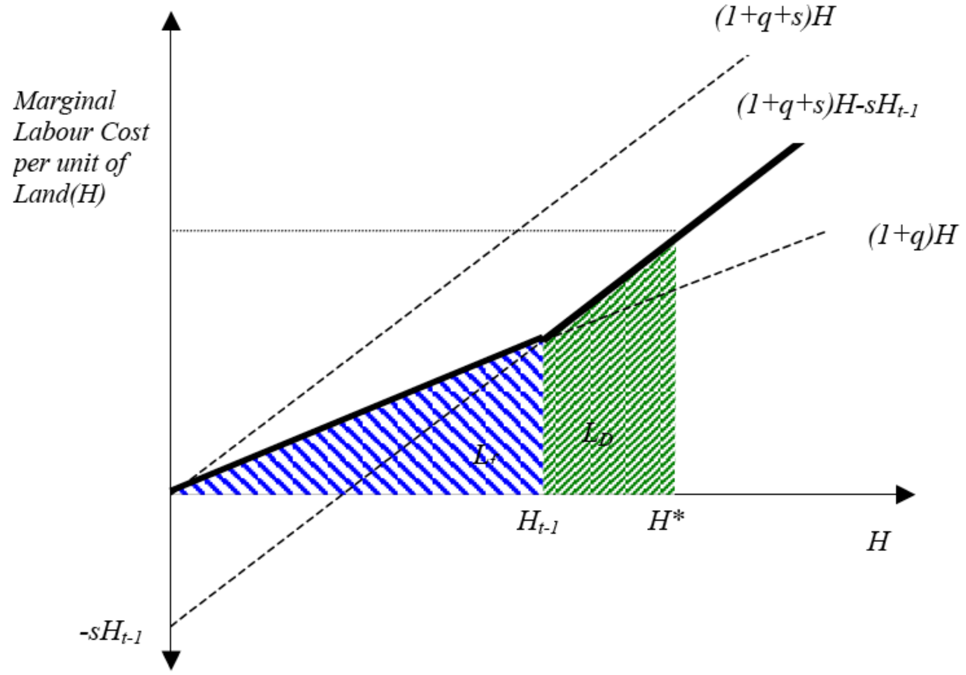


Figure 5: Calculation of community 'Scores' in well-being and deforestation space

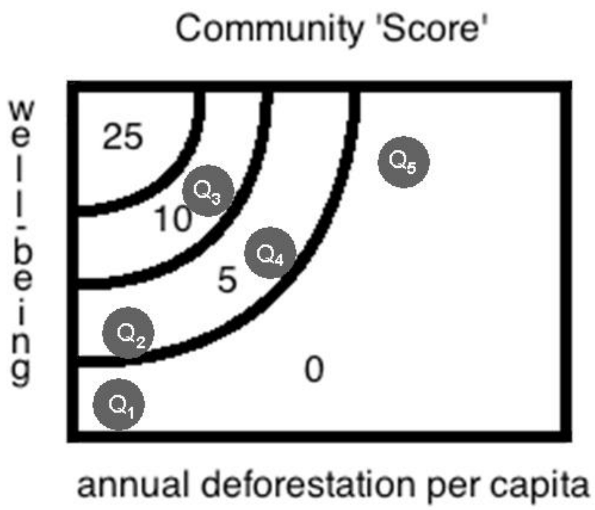


Figure 6: Reductions in deforestation can be achieved for different combinations of deforestation taxes and conservation payments

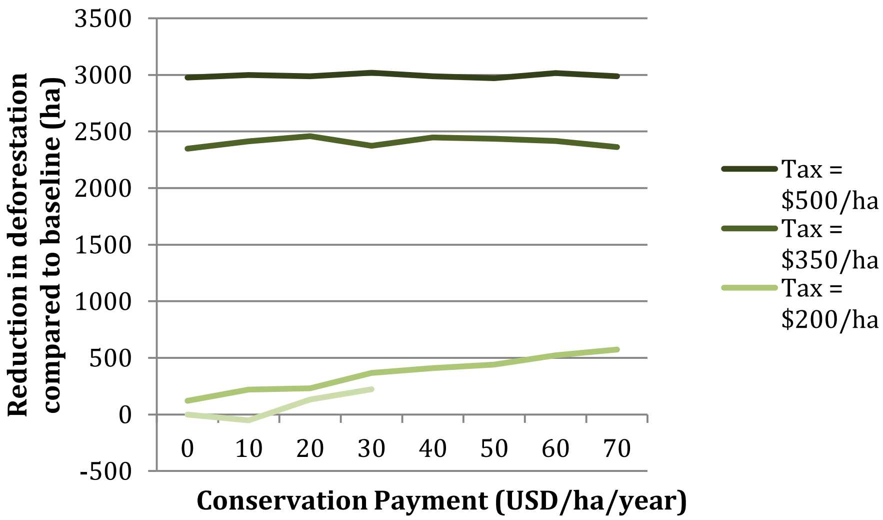


Figure 7: Score achieved for different combinations of deforestation tax and conservation payment

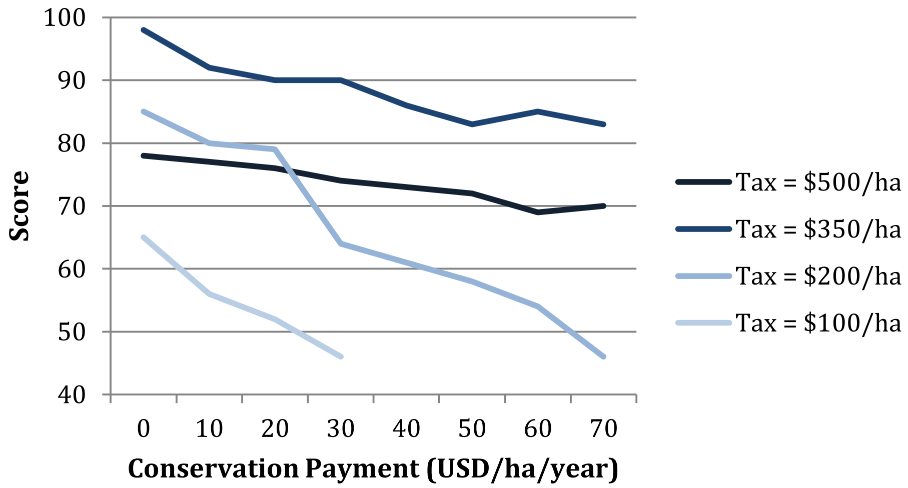


Table 1: Summary statistics from the 2010-2011 Bolivian household survey

Variable	Rurrenabaque - Reyes Obs	Mean	Std.Dev.	Rurrenabaque-Yucumo Obs	Mean	Std.Dev.	San Buenaventura - Ixiamas Obs	Mean	Std.Dev.
Property Size (ha)	45	302.14	986.34	149	53.16	102.65	96	88.76	175.92
Forest (ha)	45	185.77	639.48	149	25.94	62.24	96	47.27	102.60
Agriculture (ha)	45	2.00	2.61	149	2.94	3.02	96	3.48	3.36
Pasture (ha)	45	86.95	416.24	149	17.31	46.57	96	25.20	104.51
Fallow (ha)	45	27.43	79.87	149	6.98	9.90	96	12.81	23.67
Distance to Community (km)	45	2.63	3.92	149	1.68	2.49	96	3.64	4.69
Family Size	45	5.67	2.89	149	5.65	2.53	96	5.59	2.10
Share of land deforested	45	0.64	0.37	149	0.60	0.28	96	0.42	0.27
Sells Produce (1=Yes, 0=No)	45	1.00	0.00	149	1.00	0.00	96	0.96	0.20
Share Income from Agriculture	45	0.50	0.45	149	0.52	0.45	96	0.44	0.42
Hires Labour (1=Yes, 0=No)	45	0.53	0.50	149	0.62	0.49	96	0.76	0.43
Years in community	45	16.64	17.39	149	15.87	9.52	96	21.52	14.57
Net Income (Bs)	45	305.82	481.60	149	309.63	568.00	96	285.62	342.79
Annual Deforestation (ha)	45	3.14	5.31	149	1.92	1.63	96	2.64	2.39
Communal land title (1=Yes, 0=No)	45	0.49	0.51	149	0.26	0.44	96	0.53	0.50
Private land title (1=Yes, 0=No)	45	0.40	0.50	149	0.36	0.48	96	0.43	0.50
Land titling in process (1=Yes, 0=No)	45	0.11	0.32	149	0.38	0.49	96	0.04	0.20

Source: Leguia et al. (2011).

Table 2: Base-line simulation and effects of the Deforestation Tax (without REDD payments)

Outcome	Deforestation Tax (USD/ha) 0 (Base-line)	50	100	150	200	250	300	350	400	450	500
Total accumulated deforestation (ha)	5,905	5,790	5,683	5,463	5,332	5,143	4,790	3,457	2,817	2,817	2,817
Average annual reduction in deforestation (ha)	0	6	11	22	29	38	56	122	154	154	154
Total cattle (#)	7,794	7,598	7,402	7,019	6,831	6,506	5,878	3,383	2,298	2,298	2,298
Daily wage (USD)	7.1	7.1	7.1	7.1	7.1	7.1	7.1	7.1	7.1	7.1	7.1
Average well-being (HLY)	73	73	73	73	73	73	73	72	58	58	58
Score (0-100)	45	45	46	46	47	47	50	53	45	45	45

Note: 'HLY' denotes 'Happy Life Years.'

Table 3: Implementation of a USD 250 per hectare Deforestation Tax plus additional Public Investment or Green Jobs (without REDD payments)

Outcome	No other policy	Public Investment (USD '000 per year)				Green Jobs (# per year)		
		10	25	50	85	5	10	15
Total accumulated deforestation (ha)	5,143	5,277	5,374	-	-	-	-	-
Average annual reduction in deforestation (ha)	38	31	27	-	-	-	-	-
Total cattle (#)	6,506	6,591	6,637	-	-	-	-	-
Daily wage (USD)	7.1	7.1	7.1	-	-	-	-	-
Average well-being (HLY)	73	78	82	-	-	-	-	-
Score (0-100)	47	55	65	-	-	-	-	-

Note: 'HLY' denotes 'Happy Life Years'; - denotes 'not feasible.'

Table 4: Implementation of a USD 250 per hectare Deforestation Tax plus additional Public Investment or Green Jobs (with REDD payments)

Outcome	No other policy	Public Investment (USD '000 per year)				Green Jobs (# per year)		
		10	25	50	85	5	10	15
Total accumulated deforestation (ha)	5,143	5,277	5,374	5,505	-	5,131	5,100	-
Average annual reduction in deforestation (ha)	38	31	27	20	-	39	40	-
Total cattle (#)	6,506	6,591	6,637	6,715	-	6,507	6,508	-
Daily wage (USD)	7.1	7.1	7.1	7.1	-	7.1	7.1	-
Average well-being (HLY)	73	78	82	87	-	73	73	-
Score (0-100)	47	55	65	75	-	47	47	-

Note: 'HLY' denotes 'Happy Life Years'; - denotes 'not feasible.'