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

Lykke Andersen[a], Ben Groom[c], Evan Killick[d], Juan Carlos Ledezma[e],
Charles Palmer[c] and Diana Weinhold[c]

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Abstract: Policy interventions designed to simultaneously stem deforestation and reduce poverty in tropical countries entail complex socio-environmental trade-offs. A hybrid model, comprising an optimising, agricultural household model integrated into the 'shell' of an agent-based model, is developed in order to explore the trade-offs of alternative policy bundles and sequencing options. The model is calibrated to the initial conditions of a small forest village in rural Bolivia. Heterogeneous farmers make individually optimal land-use decisions based on factor endowments and market conditions. Endogenously determined wages and policy provided jobs link the agricultural labour market and rural-urban migration rates. Over a simulated 20-year period, the policymaker makes 'real-time' public investments and public policy that in turn impact welfare, productivity, and migration. National and local land-use policy interventions include conservation payments, deforestation taxes and international REDD payments that both impact land use directly and affect the policymaker's budget. 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: ABM, Bolivia, deforestation, land use, policy, REDD

JEL codes: Q23, Q28, Q56, R14

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* Corresponding author: Charles Palmer, Department of Geography and Environment, London School of Economics, Houghton Street, London WC2A 2AE (+44 20 7107 5093, c.palmer1@lse.ac.uk).

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[a] Institute for Advanced Development Studies (INESAD), Bolivia; [c]London School of Economics, UK; [d]University of Sussex, UK; [e]Conservation International Bolivia.

1. Introduction

For decades, deforestation and forest degradation in tropical nations have reduced supplies of forest ecosystem services (MA, 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; 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, which gives 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 a novel hybrid, comprising on the one hand, an agent-based model (the ABM ‘shell’), and an optimising, agricultural household model on the other. The latter allows households to make individually optimal land-use decisions according to their specific circumstances, e.g. landholdings, household size, as well as broader market conditions. The former allows us to define the landscape in which a community of heterogeneous households reside and make land-use decisions. Specifically, it allows for the endogenous determination of wages, which link the agricultural labour market to rural-urban migration rates, and adjustments of the state-space faced by households. This separation between the ABM shell and the optimising household allows the mayor to explore the interactions between her policy choices, the choices made by individual households, and important external drivers of change.

Using real-time information on community well-being, deforestation, macroeconomic conditions and the mayor's budget, the mayor can adjust a range of policies to try to reduce deforestation and improve welfare. 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 and deforestation taxes that both impact land use and the mayor's budget, as well as welfare.

The ABM shell thus adopts some key features from previous ABM of resource use and policy, namely the potential to run more realistic, multi-period simulations, incorporate a number of policy levers that could, in principle be implemented simulanaeously, and explore impacts across a population of heterogenous agents, e.g. Berger (2001), Evans and Kelley (2004). Building on partial equilibrium models of the household (e.g Angelsen, 1999; Ferraro and Simpson, 2002; Groom and Palmer, 2010, 2014), these features allow us to situate individual optimising agents in a more realistic, quasi-general equilibrium world. Within this, how the household allocation of labour determines land use is modelled on the basis of previous research in this area, for instance, by Groom et al. (2010), Pascual and Barbier (2007), and Shively and Pagiola (2008). Although our model represents a relatively closed economy, we simulate the possibility for international incentives for reducing emissions from deforestation and forest degradation (REDD) thus providing a bridge between general equilibrium models (Ollivier, 2012; Laing and Palmer, 2015) and ABM (Purnomo et al., 2013) that attempt to simulate the impacts of REDD at a broader scale.

The model is initialised and calibrated using rural household survey data, described in Section 2, from two small communities on the Bolivian Amazonian frontier. 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 $5,000. 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).

Our hybrid model, presented in Section 3, 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 number of potential lessons have emerged that are theoretically coherent and potentially empirically testable. We further discuss these lessons and conclude in Section 5.

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

2. The Bolivian 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.

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, 2008). For example, all of the households surveyed in this study (see below) either had clear legal title to their

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

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.

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. Specifically, we make intensive use of a survey of 290 agricultural households from three communities in the region of Rurrenabaque and Buenaventura, on the Amazonian frontier (Leguia, et al. 2011). The survey included information on property size, land use and deforestation, land tenure, labor force participation, household demographics, wealth, wages, cattle stocking and reproduction, and geographic and environmental variables. Summary statistics of the main variables of interest are presented in Table 1. In addition, the research team spent several weeks in the region interviewing local actors, validating parameters and predictions of the model, and conducting a participatory workshop in San Buenaventura (April 2012), with the participation of local farmers, cattle ranchers, loggers, teachers and the mayor of the municipality.

TABLE 1 HERE

3. The model

3a. Household optimisation

Following the theoretical typology outlined in Angelsen (1999), an initial calibration exercise using the Leguia et al. data from Rurrenabaque and San Buenaventura rejected both the 'full belly' subsistence model and the Chayanovian model of joint consumption and production with limited off-farm opportunities. Instead, a model of profit maximising agents with full access to both labour and goods markets provided a much more plausible description of these communities, and was adopted as the starting framework for our simulation model.

The main optimising 'engine' of the simulation is thus a model of the behaviour of household producer-consumers with varying access to an agricultural labour market and off-farm labour markets. The household model is described more formally in Appendix 1. Households are heterogeneous in their initial endowment of land, land productivity, and family size. Total household time (T) is divided between on-farm labour (L), local off-farm labour (L^w, where w is the wage rate), city (out-migration) off-farm labour (L^{OFF}), and leisure (l). On-farm labour is in turn is 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 output). Households can also work for wages off-farm (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 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 of interest. 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 1 illustrates the marginal cost for labour as a function of land cultivated.

FIGURE 1 HERE

We assume that each household's plot is of a fixed width. 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 1 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 1 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 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 Rurrenabaque. In particular, the literature suggests (see Faminow, 1998; Birner, 1999) that current investment in cattle is not only an investment for future returns (which could be modelled at net present discounted value today), but also as a hedge against future risk (which would require additional assumptions about relative risk aversion and future expectations of shocks), and a source of social prestige (well-being in and of itself).

Cattle also have the unique property that, unlike crops, they reproduce. We model the optimal livestock production decision in two steps; first, the intensive decision (step 1) in which a technological decision is taken about how intensively to undertake livestock farming (e.g. the stocking rate per hectare). This 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. Diminishing returns to land are modelled by assuming that livestock follow a standard logistic growth function. Fixed investment costs make potentially more productive, intensive production inaccessible for certain households. Then, the household's optimal solution to the intensive problem provides the input to the second, extensive decision (step 2) in which a decision is taken on how many hectares to ranch conditional on the stocking rate. The full cattle model is described and solved in Appendix 2.

3b. The ABM 'shell' of heuristic dynamics and general equilibrium effects

So far our household optimisation model is mostly static (except for the quasi-dynamic decision in cattle stocking); given the initial conditions and parameter values, households make a (myopic) optimal land-use decision. In theory it would be feasible to allow households to dynamically optimise over a given time horizon, but in practice this is computationally much more demanding, especially since we allow the mayor the possibility to continually adjust policies throughout the 20-year runtime of the simulation.

Instead, we use the ABM 'shell' to adjust the state-space faced by each household at the beginning of each period, as a function of the decisions taken by the household in the previous period, the decisions taken by other households (that will affect the labour supply and wage), and other changes in macro-economic conditions. For example, if more households choose to supply labour to the local market than choose to hire in labour, households are constrained and the ABM shell finds a new market-clearing (or near-clearing) wage so that in the next period the market wage faced by all households will be lower. In addition, each period a certain amount of land must be left fallow. Rather than build this in as a choice variable (difficult in the absence of dynamic optimisation), households are required in the ABM shell to leave land fallow on a regular schedule. Thus, although we forgo the opportunity of explaining fallow (we take this as given), we do incorporate the constraint via the ABM in a simple, straightforward fashion.

The ABM shell also allows us to incorporate migration and population growth into the model. Both are important both for economic and environmental outcomes and for the dynamics in the model. Population growth 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, 2008), each additional new person is allocated 50 hectares of forested land, which is appended to the household plot.

As in real life, in- and out- migration are also important determinants of how the simulated settlement evolves. Based on interviews in the region, we assume that migration into the community is mediated by a government-assisted settlement programme (INRA 2008). The number of new families arriving each year is endogenously determined within the ABM shell and increases the local population by between 0-5%, depending on the availability of land and the well-being of existing households. Specifically, we assume that households will not migrate into the community if the community 'Score' (broadly a weighted average of economic prosperity and environmental health, explained in more detail below in section 3d) falls below a particular threshold, nor will there be any in-migration if land is unavailable. However if land is available and community well-being is sufficiently high, then in-migration increases the local population by 0.1% for each one point increase in the community well-being score, up to a maximum of 5%. 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 small-farmer model. Separately, cattle numbers grow according to the cattle model.

Reflecting local realities in the region of study, migration out of the community is dominated by young people who would rather work in non-agricultural jobs. In the model, out-migration varies between 0 and 5% of the total population per year, and based on the findings from interviews with the local communities, we assume that it depends both on the level of education (positively) and the availability of non-agricultural jobs (negatively) in the community. Specifically, out-migration increases by 0.1 percentage points for every USD 2000 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 person.

The ABM shell adjusts the state-space characteristics each year based on the outcome of the previous year's decision of optimising households. New market-clearing prices and wages are determined, some land is set aside for fallow, people arrive, either naturally or through in-migration, and leave. The households 'wake up' anew, face their new initial conditions and constraints as generated by the ABM shell, and repeat the optimisation exercise. Our model thus incorporates a microeconomic model of optimisation agents, in our case agricultural households, into an ABM framework, which allows us to simulate the impacts of policy interventions across a population of agents. This is visualised as a landscape in the user interface of the model (called *Sim Pachamama,* Quechua for Sim MotherEarth - see Appendix 3).

3c. Policy Levers

The ABM shell is also the component of the model which allows for 'real time' policy adjustments. The shell provides the mayor with a host of information about the current state-space, including the average well-being of the households (explained in detail below, in section 3d), 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 across five different types of policy lever:

1. Public Investment
2. Investment in local, non-agricultural jobs (Green Jobs)
3. Deforestation Tax
4. Conservation Payments
5. 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 6000, 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.[3] When this option is active the community will receive a reward for every hectare of reduced deforestation, with a default price of USD 5000 per hectare. This corresponds to USD 10 per ton of avoided CO_2 emissions from deforestation, and can be adjusted in the model.[4] 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.

Land use and human well-being outcomes in the simulation are therefore simultaneously affected by both the decisions of the households, the evolving external economic environment, and the dynamic trajectory of policy choices made by the mayor. Policies like Conservation Payments or Deforestation Taxes will affect decision making essentially through the price of land. This allows us to make predictions about the likely effects of such policies at the individual household level as well as providing the simulation with a means of evaluating different policies at the level of the geographical region of interest. Households in turn will adjust their supply of labour to the agricultural and off-farm market, affecting wages and land use in the next period.

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[3] Bluffstone et al. (2013) discuss the practicalities of community-controlled forests participating in REDD+.

[4] Bolivian forests have the potential to release, on average, about 500 tons of CO_2 per ha, if burned.

Local policies that generate Green Jobs, for example, will similarly affect wages and household labour supply choices.

3d. Human well-being, environmental health and calculation of the 'Score'

The objective of the model is to explore trade-offs faced when simultaneously trying to reduce deforestation and increase human well-being. Furthermore, in addition to average well-being we are also interested in the *distribution* of overall well-being across income quintiles in the community. While the simulation is potentially able to output all the variables of interest each year, in practice it is more practical to provide a summary statistic of overall policy success that incorporates the objectives parsimoniously. Thus, each year the ABM shell evaluates human well-being and deforestation per capita for each quintile. The community receives five scores corresponding to the relative well-being per household and deforestation per capita of each quintile. These five quintile scores sum to the community 'Score' for that year, and the objective of the mayor is to maximise the average Score over 20 years subject to a budget constraint.

Calculating deforestation per capita is straightforward. To calculate the human well-being of each household the ABM shell evaluates a five-argument Cobb-Douglas well-being function:

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

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).

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 households in each quintile in the wealth distribution, average well-being as calculated by equation (1) and average deforestation per capita are plotted by the ABM shell 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 2, with each of the four rings earning a score of 25, 10, 5 and 0, respectively, and can also be seen in Appendix 3. The community Score is then the sum of the individual quintile scores. 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 2 HERE

In sum, the hybrid optimisation-ABM simulation model features an array of heterogeneous households, calibrated to the conditions of a small agricultural community on the Bolivian Amazonian frontier. An ABM 'shell' sets the state-space characteristics at the start of each period, determining equilibrium market-clearing wages and prices (including taxes and conservation payments, if any) and household endowments, based on the outcomes from previous household decisions and policy choices by the mayor. Households make constrained optimisation choices about land use, deforestation, and labour supply based on their endowments and the prevailing macro-environment. The mayor can then adjust any of the five policy levers based on real-time information on the community score, average well-being, total deforestation, the mayor's budget, and wages.

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 ABM shell 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 ABM shell 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, the 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, we present a number of general results for the policy choices of a mayor with the chief aim of maximising well-being (via Public Investment) before examining those of one who prioritises the reduction of deforestation (Conservation Payments) and finally one who is keen both to maximise well-being and reductions in deforestation (Green Jobs).

We begin by simulating no policy, business-as-usual (baseline) outcomes – deforestation, population growth rates, number of cattle, wage rate, well-being, and community Score – when there is a lump sum of USD 15,000 transferred by central government to the mayor for public investment each year (see Table 2). Since this is the only money entering or leaving the community, it represents a very localised and self-contained economy. Consistent with the Bolivian case, the mayor cannot borrow in order to finance policy. We then show, in Table 2, the same outcomes when individual policies – Public Investment, Conservation Payments, and Green Jobs – are implemented in the first year of the simulation, 2012. Note that all policies, including Public Investment, are implemented on top of the annual transfer of USD 15,000 from the central government.

TABLE 2 HERE

The first thing to note about the results in Table 2 is that simulating the model in the absence of policy allows it to run for the full 20 years. Once policies are implemented, the mayor tends to run out of money and break the budget constraint within a few years (see the row 'Year simulation ends' in Table 2). Rising Public Investment appears to increase average well-being and the Score. Yet, the former remains below the baseline level while the latter is constantly higher. Against the baseline none of the policies, including the Conservation Payment, appear to reduce deforestation. However, further comparison of impacts across policies and also within policies, e.g. different levels of Conservation Payment, is complicated by the fact that the mayor breaks her budget constraint at different points in time. These results clearly suggest a need for additional sources of funding in order to allow for policies to work over the full 20-year period, hence enabling a better comparison of policy impacts.

The mayor is only able to raise revenue from two possible sources: a Deforestation Tax and an International Incentive for reducing emissions from deforestation and degradation. While both 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 3 starting with the baseline case, i.e. where the Tax is set at zero.

TABLE 3 HERE

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 constant. 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 USD400 per hectare, however, there is a sudden sharp drop both in deforestation and well-being (Table 3). 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. 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. 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 4, we set the Tax at USD 50 per hectare and show what happens when we implement Public Investment and Green Jobs. These policies are implemented independently, again in the first year, by simply repeating the values used in Table 2.

TABLE 4 HERE

Comparing the results presented in Table 4 with those in Table 2, it is clear that the mayor stays within the budget constraint far longer, in fact for the whole 20-year period, at least until the level of Public Investment goes beyond USD 10,000 per year (on the top of the USD 15,000 transferred by the central government). Deforestation and cattle numbers appear to rise with Public Investment despite the Deforestation Tax. Well-being also increases, which drives higher community Scores. This reflects the fact that the Tax is mainly paid by the wealthier (larger) cattle ranchers who need much more cleared land than subsistence farmers. It therefore acts as a kind of 'Robin Hood' tax, with the revenues redistributed from the wealthiest to the poor through Public Investment, hence reducing inequality. Given how quickly the budget constraint is breached, a USD 50 Tax is clearly insufficient for investment in Green Jobs, even if only to create five new jobs per year.

As demonstrated in Table 4, the sequence of policies is critical: the mayor cannot achieve a good outcome with a single set of fixed policies at the start of the simulation. Expensive investments, such as the creation of Green Jobs, have to be introduced gradually as the mayors' revenues increase. Indeed, the Green Job policy is really only an option after having received substantial revenues from International Incentives for reducing deforestation (see below). If funds are only available from the Deforestation Tax, a possible strategy is for the mayor to implement a maximum tax on deforestation and save for 10 years, in order to create five Green Jobs during the second decade. While this strategy successfully reduces deforestation, well-being suffers and the community Score tends to be quite low.

Staying with the Deforestation Tax, we now consider a mayor who is focused on reducing deforestation and implements a Conservation Payment financed by the Tax. 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 3 shows that increasing the size of the Payment will contribute to further reductions in deforestation, but only if the Tax is low. Farmers and ranchers in the model calculate how much land they are going to need for the next 20 years. The land they volunteer in exchange for 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.

FIGURE 3 HERE

The Deforestation Tax cannot be too low because otherwise there is insufficient money in the mayor's budget to finance 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.[5] 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 4 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 constraint is more binding 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 4 HERE

In sum, if the mayor does not implement a Deforestation Tax early on, she will breach her budget constraint very soon after implementing one or more of the other policies. Yet even at high Tax levels, it is challenging to stay within the budget constraint 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. A price of reduced CO_2 emissions set at USD 10/tCO_2 corresponds to a relatively large sum of USD 5,000/ha of avoided deforestation. 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. Reduced deforestation, whether induced by Deforestation Taxes, Conservation Payments or International Incentives, provides some positive effects for well-being. But by itself does not 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.

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 the essential features of agricultural and economic decisions among smallholders in the Amazon Basin in Bolivia. While our hybrid dynamic optimising- heterogeneous- agent based model 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

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[5] 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.

households endogenously choose how much land to cultivate, how large a cattle herd to maintain, and whether to expand at the intensive margin through input choice or 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 constraint that 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 ABM 'shell' program. Continuously variable policy adjustments by the mayor alter the trajectory across both economic and environmental outcomes. While useful for exploring the impacts of different policies over time, we do assume that perfect information on those impacts is received by the mayor on an annual basis. In reality, we acknowledge that there are costly informational requirements that may not be met in poor, rural communities, and that the ability to respond instantaneously with policy adjustment overlooks the potential for policy inertia.

In spite of these limitations, our model is methodologically innovative and highly interactive. After much experimentation in choosing and adjusting policy levers throughout the 20-year simulation, a number of interesting and consistent predictions and implications have emerged, especially in relation to policy bundling and sequencing. 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.

The 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 the deforestation reduction forward to the extent that a surplus need not be generated in the first few years. In a setting like Bolivia our model usefully illustrates the scope for reducing deforestation. For example, we assume, based on Bolivia's settlement policy, that the government allocates a 50 hectare plot of forest to each new/arriving family. Thus, in attempting to make the model as realistic as possible, we overlook a policy change that might otherwise feature in a model of a rational mayor aiming to reduce deforestation, namely to remove this allocation.

In conclusion, our model has proven to be a useful tool for exploring policy choices and trade-offs. We have made *Sim Pachamama* publicly available and open-source, so parameters can be adjusted or re-calibrated to other settings. In addition the hybrid ABM 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 ABM shell 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:

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

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:

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

$\Pi^*(p,w,)$ 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 $(\mu > 0)$, the deforestation decision is evaluated as in previous models. Where L_{t-1}^{f} 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:

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

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. Labour costs for harvesting cattle are given by $c(R, X) = cRX$, and are determined by the size of the herd X as well as the amount that is harvested, 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:

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

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 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:

$$H(R; X) = p_c R - cRX + \lambda(\sigma X + \mu X^2 - R)$$

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 $a = (p_c 2\mu + cr - 2\sigma)$, $b = -3\mu$ and $d = p_c(\sigma - r)$, are collections of the parameters. The numerical examples below illustrate the solution to this problem for households with differing livestock technology: an intensive farm and an extensive farm.

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), labour used in livestock (L_C) and livestock harvest (R) of the form: $H = \theta X$, $L^C = \gamma X$, and $R = \phi L_C$. 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) is θ^{-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) and labour (L_C)[6], 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:[7]

$$\max_H \Pi = p_C \frac{\varphi\gamma}{\theta} H - c\left(\frac{\varphi\gamma}{\theta} H\right)^k + p_H\left(\bar{H} - H\right) - w\frac{\gamma}{\theta} H - F_C$$

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

$$H^* = \frac{\theta}{\phi\gamma}\left(\frac{p_C - w\phi - p_H \frac{\phi\gamma}{\theta}}{kc}\right)^{\frac{1}{k-1}}, R^* = \frac{\phi\gamma}{\theta} H^*, L_C^* = \frac{\gamma}{\theta} H^*$$

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 labour (γ); iv) the labour requirement 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. Wages (w) and the price of land

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[6] Other variables inputs can also be considered, such as feed.

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

(p_H) affect land in slightly different ways. The effects on land translate linearly into aggregate harvest (R), labour requirements (L_C) 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 θ, γ, 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:

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

Numerical example 1 (The Extensive Farmer): For parameter values: $\sigma = 0.25$, $\mu = -0.1$, $r = 0.05$, $p = 600$, $c = 0.1$, the carrying capacity per hectare 2.5, the maximum sustainable yield is 1.25 per hectare and the optimal stock and harvest are $X^* = 1.198$ $R^* = 0.156$

Numerical Example 2 (The Intensive Farmer): For parameter values: $\sigma = 0.5$, $\mu = -0.1$, $r = 0.05$, $p = 500$, $c = 0.10$. Here the parameters of the growth function differ now, as do the costs of harvest/management. In short intrinsic growth is higher $(\sigma = 0.5)$, and hence MSY and Carrying Capacity are respectively 2.5 and 5, that is they have doubled. The cost parameter for harvest has increased to reflect greater cost of intensive activities: $c = 10$. Here the solution is: $X^* = 2.243 \quad R^* = 0.618$

Solution to Livestock Problem Step 2

The maximisation problem is:

$$\max_H \Pi = p_C \frac{\varphi\gamma}{\theta} H - c\left(\frac{\varphi\gamma}{\theta} H\right)^k + p_H\left(\bar{H} - H\right) - w\frac{\gamma}{\theta} H - F_C$$

The Solution is:

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

From which it is straightforward to derive the remaining solutions.

Numerical Example 3 (The extensive decision):

The solution to the intensive problem provides the input to the extensive problem. From the linear relationships between labour, harvest, land and stock we have: $H = \theta X \Rightarrow \theta^{-1} = X / H$, that is, the number of cattle per hectare. The solution for the intensive and extensive farmers respectively are: $1/\theta^I = 2.24, \quad 1/\theta^E = 1.2$. Furthermore, we know that $R = \phi\gamma X \Rightarrow \phi\gamma = R / X$, which in the intensive and extensive cases are given by: $\phi^I\gamma^I = 0.276, \quad \phi^E\gamma^E = 0.130$. So the aggregate harvest is lower for the extensive rancher. The unknown parameters are φ and γ which indicate the labour requirement per head of cattle, and the labour requirement per unit of harvest. The choice of one automatically defines the other. Defining $\gamma^I = 0.02, \ \gamma^E = 0.04$ which means that on average one person can look after 50 cattle in the intensive case and 25 cattle in the extensive case. This means that: $\phi^I = 13.8, \ \phi^E = 3$. This implies that one person can harvest nearly 14 cattle in the intensive case, and 3 cattle in the extensive case. This leads to the following solutions.

Extensive cattle farming:

For parameter values: $c = 10. k = 1.5. \gamma = 0.04, \phi = 3 \ \theta = 0.833, \ p_H = 0, \ p_C = 300 \ \ w = 30$.

The solutions are: $H^* = \frac{\theta}{\varphi\gamma}\left(\frac{p_C - w\varphi - p_H \frac{\varphi\gamma}{\theta}}{kc}\right)^{\frac{1}{k-1}} = 1360.6 \quad R^* = \frac{\phi\gamma}{\theta} H^* = 196$

$L_C^* = \frac{\gamma}{\theta} H^* = 65.35 \quad X^* = \frac{1}{\theta} H^* = 1633$. This is a big farm, with over 1,000 cattle.

Intensive cattle farming:

With all parameters identical except $\gamma = 0.02, \phi = 13.8, \theta = 0.45, \ p_C = 700$,

the solutions are:[8] $H^* = 592.7$ $R^* = 363.5$ $L_C^* = 26.32$ $X^* = 1317.1$
This is a big farm, with over 1,000 cattle, but more intensively farmed.

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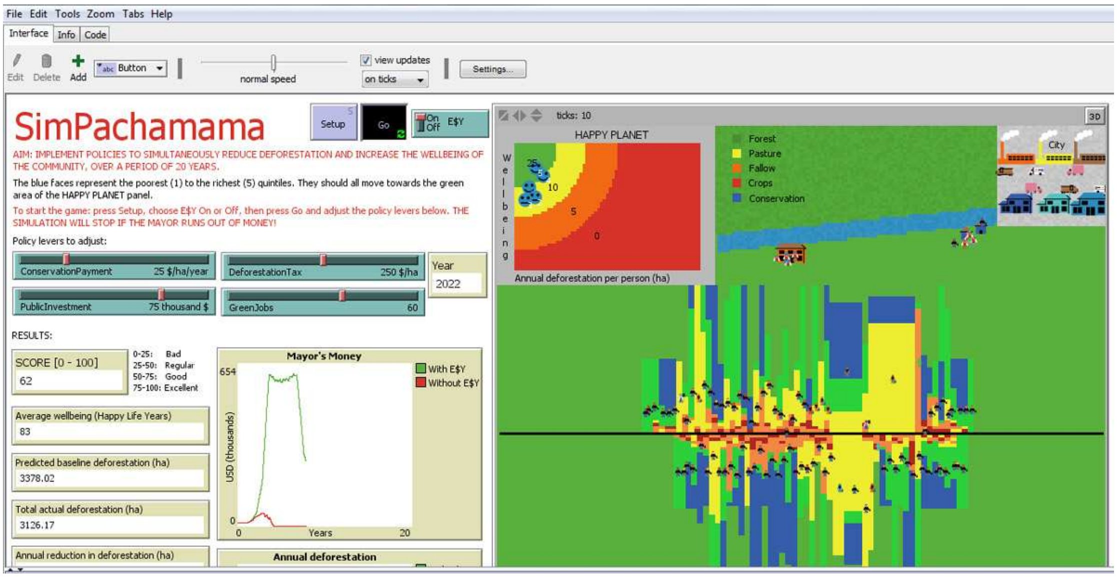
[8] For a maximum it must be the case that whatever is raised to the power $\frac{1}{k-1}$, must be positive. This is satisfied if $p_C - w\phi - p_H \dfrac{\phi\gamma}{\theta} > 0$

Appendix 3

Figure 3.1: 2D and 3D screen shot from the model, called 'SimPachamama'



AIM: IMPLEMENT POLICIES TO SIMULTANEOUSLY REDUCE DEFORESTATION AND INCREASE THE WELLBEING OF THE COMMUNITY, OVER A PERIOD OF 20 YEARS.

The blue faces represent the poorest (1) to the richest (5) quintiles. They should all move towards the green area of the HAPPY PLANET panel.

To start the game: press Setup, choose E$Y On or Off, then press Go and adjust the policy levers below. THE SIMULATION WILL STOP IF THE MAYOR RUNS OUT OF MONEY!

Policy levers to adjust:

ConservationPayment 25 $/ha/year

DeforestationTax 250 $/ha

Year 2022

PublicInvestment 75 thousand $

GreenJobs 60

RESULTS:

SCORE [0 - 100] 62

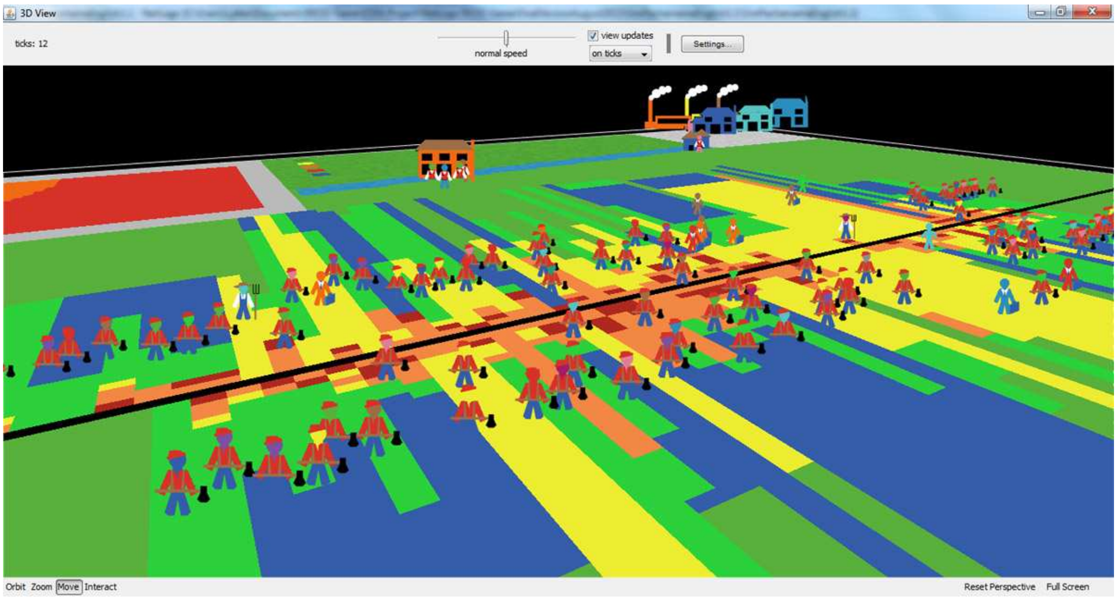
0-25: Bad
25-50: Regular
50-75: Good
75-100: Excellent

Average wellbeing (Happy Life Years) 83

Predicted baseline deforestation (ha) 3378.02

Total actual deforestation (ha) 3126.17

Annual reduction in deforestation (ha)



ticks: 12

Note:

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

Tables and Figures

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

	Rurrenabaque - Reyes			Rurrenabaque-Yucumo			San Buenaventura - Ixiamas		
Variable	**Obs**	**Mean**	**Std.Dev.**	**Obs**	**Mean**	**Std.Dev.**	**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: Baseline simulations with and without policies requiring finance

Outcome	**No policy**	**Public Investment (USD '000 per year)**				**Conservation Payment (USD per ha per year)**						**Green Jobs (# per year)**
		5	**10**	**15**	**20**	**5**	**10**	**15**	**20**	**25**	**30**	**5**
Total deforestation (ha)	5,905	2,746	2,512	2,396	2,356	2,731	2,648	2,506	2,506	2,396	2,395	2,358
Annual reduction in deforestation (ha)	0	0	0	0	0	0	0	0	0	0	0	0.61
Annual population growth rate (%)	1.75	2.23	2.08	2.39	2.39	2.04	2.08	0.79	0.79	1.6	1.6	-1.83
Total cattle (#)	7,794	2,881	2,423	2,167	2,167	2,876	2,697	2,421	2,421	2,166	2,166	1,925
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	7.3
Average well-being (HLY)	73	68	69	70	71	66	65	65	65	65	65	64
Score (0-100)	45	47	48	53	53	43	43	45	45	48	48	40
Year simulation ends	2032	2016	2014	2013	2013	2016	2015	2014	2014	2013	2013	2012

Note: 'HLY' denotes 'Happy Life Years'

Table 3: Implementation of the Deforestation Tax

Deforestation Tax (USD/ha)	**0**	**50**	**100**	**150**	**200**	**250**	**300**	**350**	**400**	**450**	**500**
Total deforestation (ha)	5,905	5,790	5,683	5,463	5,332	5,143	4,790	3,457	2,817	2,817	2,817
Annual reduction in deforestation (ha)	0	13	26	35	41	102	133	247	287	287	287
Annual population growth rate (%)	1.75	1.75	1.17	1.17	1.17	1.17	1.17	1.17	-1.14	-1.14	-1.14
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
Year simulation ends	2032	2032	2032	2032	2032	2032	2032	2032	2032	2032	2032

Note: 'HLY' denotes 'Happy Life Years'

Table 4: Implementation of a USD 50 per hectare Deforestation Tax plus Public Investment or Green Jobs

Outcome	**No other policy**	**Public Investment (USD '000 per year)**				**Green Jobs (# per year)**
		5	**10**	**15**	**20**	**5**
Total deforestation (ha)	5,790	5,906	5,960	2,652	2,395	2,394
Annual reduction in deforestation (ha)	13	1.38	1.42	0	0	0.33
Annual population growth rate (%)	1.75	1.05	1.38	2.08	2.39	1.6
Total cattle (#)	7,598	7,693	7,717	2,506	2,163	2,162
Daily wage (USD)	7.1	7.1	7.1	7.1	7.1	7.3
Average well-being (HLY)	73	77	78	70	71	65
Score (0-100)	45	49	52	50	53	48
Year simulation ends	2032	2032	2032	2015	2014	2013

Note: 'HLY' denotes 'Happy Life Years'

Figure 1. The marginal cost of labour as a function of distance from the road

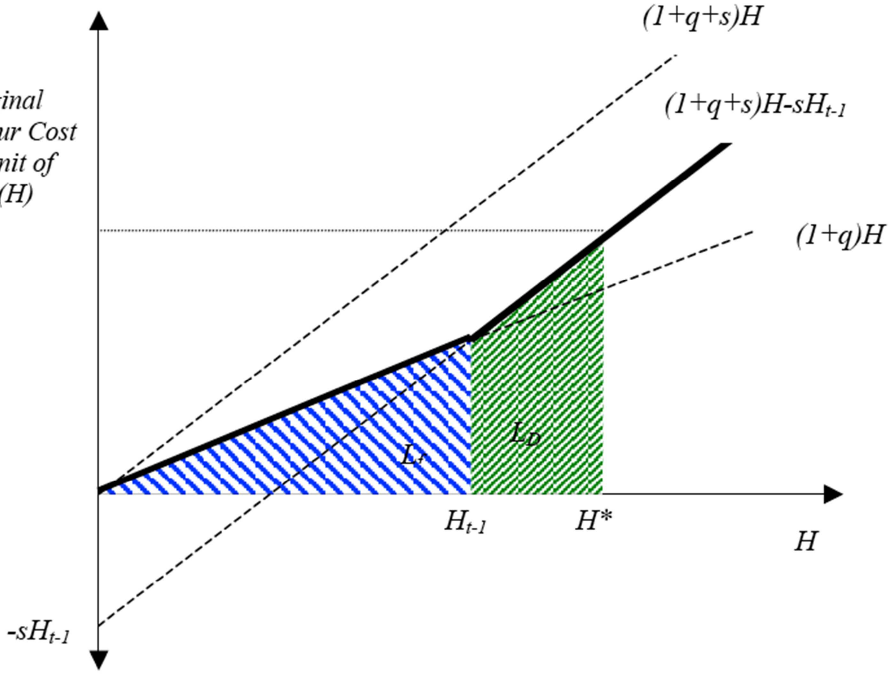


Figure 2: Calculation of community 'Scores' in well-being and deforestation space

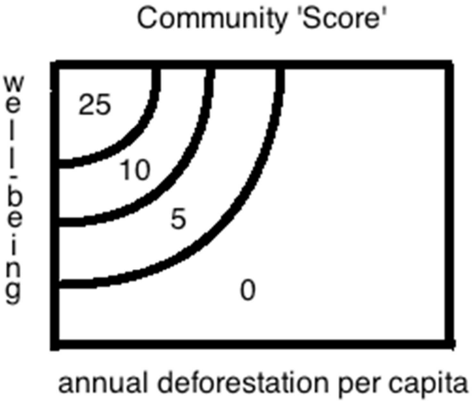


Figure 3: Reductions in deforestation can be achieved for different combinations of deforestation taxes and conservation payments

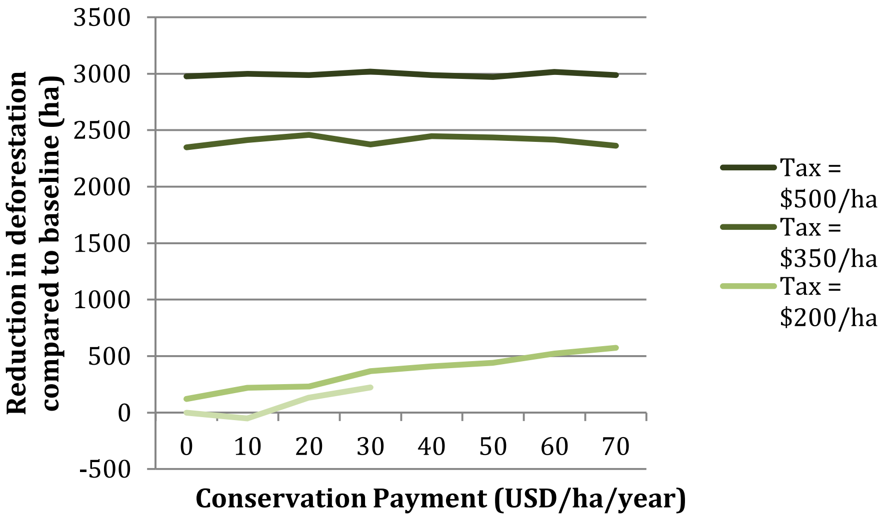


Figure 4: Score achieved for different combinations of deforestation tax and conservation payment