Agent-based model of repeated conservation auctions in low-income countries: ODD+D Protocol

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We describe our model according to the ODD+D Protocol, extended by Mueller et al. (**?**). This standard description of agent-based models introduces decision-making, adaptation and learning of the agents in a comprehensive and clearly structured way; it incorporates the theoretical and empirical background of model design and assumptions.

1 Overview

1.1 Purpose

The purpose of our study is to explore the extent to which non-targeted repeated auctions can provide biodiversity conservation cost-effectively, while alleviating poverty. Targeting landholders in order to integrate both goals is claimed to be overambitious and underachieving because of the trade-offs they imply. The model is designed to assess policy-making; its results offer insight on the possible outcomes that can derive from implementing conservation auctions in low-income countries, where landholders are likely to be risk averse and to face uncertainty.

1.2 Entities, state variables and scales

Our **farm-scale** model considers two types of **entities**: an environmental agency and landholders. The environmental agency is assumed to have the goal of maximizing the environmental value derived from conservation. It does so by offering direct payments to landholders wiling to allocate their land to conservation. It is constrained by a fixed budget in every period. Landholders are assumed to maximize the profits derived from their land use. They are offered payments as a compensation for allocating their land to conservation, in which case they are assumed to incur opportunity costs.

The **state variables** are exogenous factors or drivers of our model. These are the budget available for the agency to contract landholders, the number of landholders who could potentially participate in the conservation scheme, their opportunity costs of conservation and the presence of uncertainty in regard to these costs.

1.3 Process overview and scheduling

The environmental agency offers contracts to landholders in every period over a time span of 40 periods. Contracts are allocated by means of three different mechanisms: fixed payments, uniform auctions and discriminatory auctions. The processes differ according to the allocation mechanism. This processes are repeated in each period t. We describe them in the following and provide diagrams to visualize the scheduling of the actions undertaken by the agents in each period. The rectangles symbolize an agent and the rhombuses symbolize actions. The red arrows symbolize both exogenous and endogenous information flows.

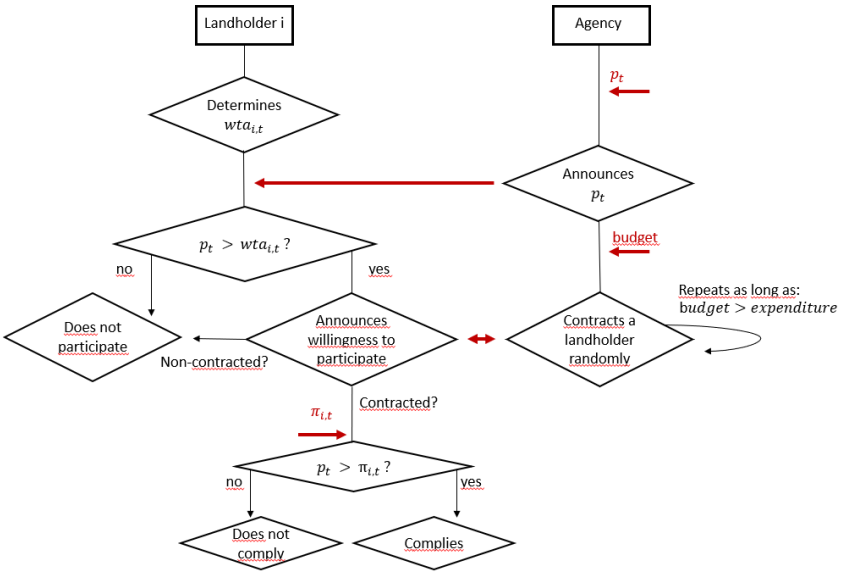

Figure 1: Allocation process of fixed payments

Fixed payments are determined exogenously and are announced by the agency. Landholders determine their minimum willingness to accept for participation. Landholders whose minimum willingness to accept $wta_{i,t}$ is exceeded by the fixed payment p_t announce their willingness to participate in the conservation scheme. The agency contracts a landholder randomly. This action is repeated until the budget is exhausted. In the last step, uncertainty is resolved and landholders learn their actual opportunity costs. Only those landholders whose actual costs are covered by the payments comply with the contract requirements.

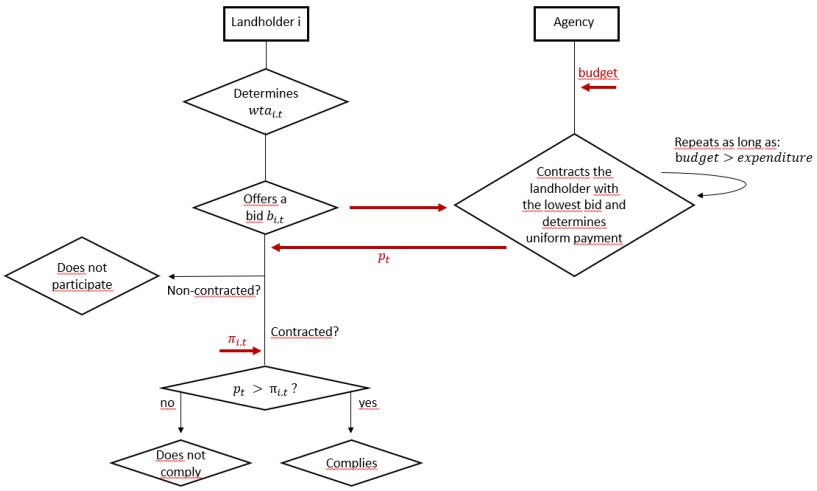

Figure 2: Allocation process of uniform auctions

The payments in **uniform auctions** are determined endogenously by the lowest rejected bid. Landholders determine their minimum willingness to accept for participation in the conservation scheme. In the next step, they offer this value as a bid $b_{i,t}$. The agency contracts the landholder offering the lowest bid. This action is repeated until the fixed budget is exhausted. Then, the agency announces the uniform payment. Uncertainty is resolved in the last step, landholders learn their actual opportunity costs, which determine their compliance.

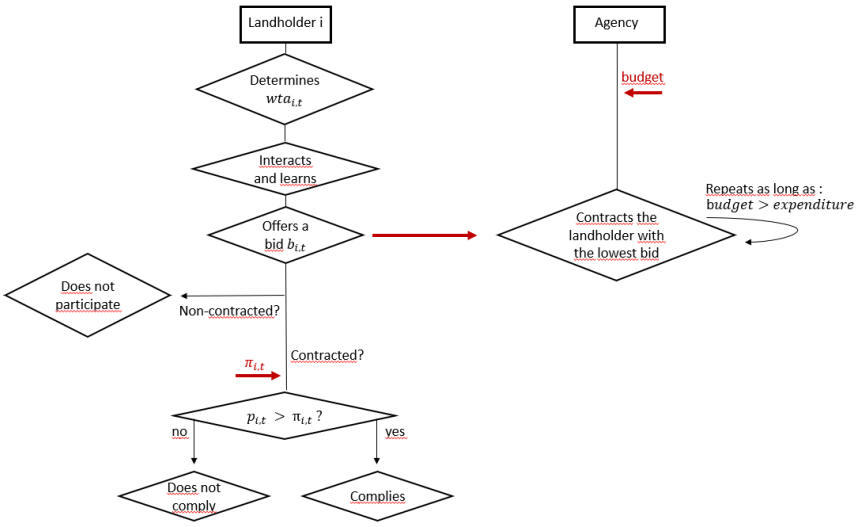

Figure 3: Allocation process of discriminatory auctions

In **discriminatory auctions**, payments are determined by the individual bids, such that every contracted landholder receives a different payment. Landholders determine their minimum willingness to accept for participation. Then, they interact with their acquaintances, exchange information, and formulate a bid accordingly. Bids are announced and the agency contracts the landholder offering the lowest bid. This action is repeated as long as the budget allows to contract a further landholder. Uncertainty is resolved in the last step. The actual opportunity costs determine their compliance.

2 Design concepts

2.1 Theoretical and empirical background

Our model builds up on the model proposed by Hailu and Schilizzi (**?**). Hailu and Schilizzi (**?**) simulate a scheme where conservation payments are paid to landholders in order to protect biodiversity. The authors compare the performance of repeated discriminatory auctions with fixed payments, assuming that bidders learn over time through reinforcement learning.

We extend the model of Hailu and Schilizzi (**?**) by including uniform auctions and a social network through which landholders can interact. In our model, instead of learning through reinforcement, landholders are assumed to learn from their own experiences and social interaction. A similar learning algorithm can be found in Lundberg et al. (**?**). The relative extent to which landholders overbid is assumed to depend on their position in the distribution of the costs, following (**?**). The bidding strategies are based on the theoretical and empirical literature on conservation auctions (**?????**). In uniform auctions, bidders make offers close to their costs (**?**); in discriminatory auctions, bidders make offers that exceed their costs, and repetition leads to higher offers over time (**?**).

We assume wealth to be correlated with the opportunity costs of conservation. Poor landholders are likely to face low opportunity costs of conservation if they possess marginal lands, are strongly capital and technology-constrained, and labor remuneration is low (**?**). Landholders are assumed to be risk averse and to face uncertainty in regard to their future opportunity costs, and they are assumed to be willing to accept contracts with low payments as an insurance to even lower future opportunity costs, following the observations of Ajayi et al. (**?**) and Khalumba et al. (**?**).

The model is not based on empirical data. We assume the same parameter values as Hailu and Schilizzi (**?**) for the baseline setting. We model three different scenarios, one for each allocation mechanism, respectively; and we explore eight different settings varying the level of competition among landholders and the level of uncertainty. The different settings do also serve as a sensitivity analysis shedding light on the robustness of the model.

2.2 Individual decision-making

The environmental agency maximizes the environmental value. The latter is described by the area allocated to conservation, as the model assumes an homogeneous provision of environmental services. Thus, constrained by a fixed budget, the agency contracts those landholders providing conservation for the least costs.

Landholders maximize the profit derived from their land use. They are offered payments if they allocate their land to conservation. The latter implies incurring opportunity costs, the foregone profit from the second best land use. Their opportunity costs of participation in the conservation scheme are described by $\pi_{i,t}$. This value is assumed to be different for every landholder i and to change in every period t. Landholders are assumed to face uncertainty in regard to these costs; they are assumed not to know the exact costs prior to implementing the contract requirements.

Landholders are moreover assumed to use the conservation contracts as an option contract in order to counteract this uncertainty. Therefore, they are assumed to be willing to accept contracts with payments that are below their expected opportunity costs. Their minimum willingness to accept for participation in the scheme can be thus interpreted as a certainty equivalent. The certainty equivalent is the monetary value that guarantees them the same expected utility as their expected income from the conventional land use, and is described in equation **??**. Landholders approximate their future opportunity costs with their current ones. The amount x_i is the risk premium, the amount they are willing to give up in order to insure themselves against uncertainty.

$$wta_{i,t} = E[\pi_{i,t}] - x_i \tag{1}$$

The decision-making processes of the agents depend on the allocation mechanism. In fixed payments schemes, landholders state their willingness to participate as long as the payment exceeds their minimum willingness to accept. The agency selects landholders randomly until the budget is exhausted. If contracts are allocated by means of uniform auctions, landholders offer a bid equal to their minimum willingness to accept, and the agency contracts those with the lowest bids until the budget is exhausted. In discriminatory auctions, landholders are assumed to formulate bids according to the algorithm described below, and the agency is contracts those landholders offering the lowest bids until the budget is exhausted.

2.3 Learning

Landholders learn from their own past experiences and from the experiences of others through social interaction. They interact in every period with their acquaintances, and exchange information about their pay-offs. This diffusion of information allows them to adapt their expectations about the bid cap over time in discriminatory auctions. Landholders are assumed to adapt their bidding strategy over time, based on the highest payment they have information about.

If a landholder has information about an accepted bid that was higher than her own (or higher than her own minimum willingness to accept if not contracted), she will have an incentive to increase her bid in the following period in order to increase her rent. If, however, the highest accepted bid she has information about is lower than her own, she could be a marginal winner, therefore she will have an incentive to lower her bid in the following round in order to secure participation.

This learning algorithm is described by equations **??** and **??**. The term $b_{i,t-1}$ describes the last bid made by a landholder i. The term $b_{j,t-1}$ describes the highest accepted bid landholder i has information about. The difference between these values is described by the gap in equation **??**. If the latter is positive, landholder i will increase her bid in the next period according to equation **??**. If the gap is negative, she will lower it according to the same equation (**?**).

$$\triangle_{i,j} = b_{j,t-1} - b_{i,t-1} \tag{2}$$

$$b_{i,t} = b_{i,t-1} + \frac{\triangle_{i,j}}{2} \tag{3}$$

2.4 Individual sensing

The environmental agency is assumed to sense the available budget and the environmental value derived from conservation. If contracts are allocated by means of fixed payments, it is assumed to sense landholders' willingness to participate in the conservation scheme; if contracts are allocated by means of auctions, it is assumed to sense their bids.

Landholders are assumed to sense their (exogenously given) real opportunity costs of conservation only after uncertainty is resolved at the end of each period. They are assumed to sense the exogenously given fixed payment offered by the agency and, if contracts are allocated by means of discriminatory auctions instead, they are assumed to sense the last (endogenously derived) bid of their acquaintances and whether they received a contract or not. This information is used to adapt their own bidding strategies.

2.5 Individual prediction

Landholders are assumed to use the opportunity costs they incurred in the previous period as an approximation of the expected costs in the current period in order to formulate their minimum willingness to accept (equation **??**). If their actual opportunity costs exceed their conservation payment, landholders are assumed not to comply with the conservation contract.

2.6 Interaction

Landholders interact directly with the agency and with other landholders they are connected to in the social network. They exchange information about their past bids and their contractual status. We assume landholders to be embedded in a social network with a commonly found small-world structure, identified by Watts and Strogatz (**?**). This type of network is characterized by a high connectivity with a small number of connections. These social networks are found in settings where landholders are connected to their neighbors, and where most connections do not involve separation by great distances (**?**). The presence of a few long-range links, meaning connections between landholders from different neighborhoods, allows a rapid spread of information throughout the population (**??**). Assuming this network structure is appropriate because residents in rural areas are shown to make more use of informal supportive neighborly relationships (**?**). We implement the Watts-Beta-Small-World Generator by Jung Project and Nick Collier, a graph generator that produces a small world network using the beta-model, as proposed by Duncan Watts (**?**). It starts with one-dimensional ring lattices in which each landholder has k neighbors with similar opportunity costs and a probability β to know landholders from other neighborhoods.

2.7 Heterogeneity

Landholders are assumed to be heterogeneous in terms of their opportunity costs of conservation and homogeneous in terms of the environmental value provided by their conservation activities, as well as their amount of land. They are moreover homogeneous in their decision-making.

2.8 Stochasticity

Some processes in the model include randomization. The initial opportunity costs of conservation are uniformly distributed in a range between 0 and 1. These are assumed to change in every period, following a normal distribution with a mean value equal to the initial costs and a certain standard deviation described by σ. A low value of σ indicates that future opportunity costs will tend to be close to the expected costs; a high value indicates that they will be spread out over a wider range. Thus, σ determines the degree of uncertainty faced by all landholders. A value equal to zero implies that landholders do not face uncertainty. Landholders' risk premium x_i, the amount they are willing to give up in order to insure themselves against uncertainty, is uniformly distributed within the range $[0; \sigma]$ and is assumed to remain constant over time. It accounts for differences in the risk preferences of landholders.

2.9 Observation

The extent to which auctions can provide biodiversity conservation is measured by the number of contracted landholders that comply with the contracts. In order to assess the extent to which auctions can induce pro-poor effects, we observe the information rents paid to and the opportunity costs of participating landholders. The information rents are defined as the sum of the individual differences between payments (p_i) and opportunity costs (π_i), as described in the following equation. The higher the information rents and the lower the opportunity costs of the landholders receiving them, the higher the pro-poor effects of the payments.

$$\text{information rents}_t = \sum_{1}^{N_t} (p_{i,t} - \pi_{i,t}) \tag{4}$$

3 Details

3.1 Implementation details

We used the software Repast Simphony 2.3.1 developed by North et al. (**?**) in the operating system Microsoft Windows and Java 8. Repast Simphony is an open source agent-based modeling and simulation platform that simplifies model creation and use. It supports the development of flexible models of interacting agents.

3.2 Model accessibility

3.3 Initialization

The baseline **setting A** consists of a population of 100 landholders, each of which is endowed with one unit of land, assumed to provide an homogeneous environmental benefit equal to 1. The opportunity costs are uniformly distributed in a range between 0 and 1. The fixed budget equals 15 and the fixed payment equals 0.5. We assume the uncertainty parameter σ to equal 0.3. Every landholder has 2 neighbors and a 20 percent probability of knowing other landholders in other neighborhoods. This setting is run for three different scenarios, representing each one allocation mechanism.

We consider seven alternative settings in order to investigate how the results are influenced by the assumptions made in the baseline setting A. Therefore, we vary the population, the budget restriction, and the level of uncertainty. Exploring the changes in the results under these settings allows us to determine the impact of these variables on the performance of auctions, and thus to test the robustness of the model's results. Moreover, it allows us to answer the question of how relevant uncertainty and competition are for achieving the goal of conservation and poverty

alleviation simultaneously. **Setting B** considers a high level of competition, where the agency is given a budget equal to 5 and the population consists of 150 landholders; **setting C** considers a low level of competition with a budget equal to 25 units and a population of 50 landholders; **setting D** considers the same level of competition as the baseline setting A, but a high uncertainty, where the parameter σ equals 0.6; **setting E** considers both a high level of competition and a high level of uncertainty; **setting F** considers a low level of competition and a high level of uncertainty; in **setting G**, on the contrary, we assume landholders not to face uncertainty regarding their opportunity costs of conservation and the level of competition among landholders in this setting is the same as in the baseline setting A; **setting H** considers a high level of competition without uncertainty; and **setting I** considers a low level of competition without uncertainty.

3.4 Input data

The model does not use input data.

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