ODD Protocol for the SESPES model

The model description follows the ODD (Overview, Design concepts, Details) protocol for describing individual- and agent-based models in its updated version (Grimm et al., 2010).

1. Purpose

Background. Incentives policies for environmental conservation purposes under the label of payment for ecosystem services (PES) gained international attention with the publication of the Millennium Ecosystem Assessment (MEA) in the 2000s and show a solid expansion in recent years with China and America Latina taking the lead (Salzman, Bennett, Carroll, Goldstein, & Jenkins, 2018). With its spread, a fierce debate in the academic literature started about the optimal design of such policies (Wells, Ryan, Fisher, & Corbera, 2020; Wunder et al., 2020, 2018). So far, several studies have compared schemes and provided an array of design principles for PES schemes. However, the majority of these studies compare examples from mainly developing countries with few recent exceptions (see e.g. Capodaglio & Callegari, 2018). One of the conflicts with such comparisons is the high interaction that context play in the effectiveness of PES policies –including the environmental, socio-economic and politic contexts (Jack, Kousky, & Sims, 2008). Thus, the design principles applicable to developing countries for mere geo-political reasons may not be applicable to other areas such as in Europe.

Purpose. The purpose of the proposed agent-based model is to intervene in the debate about PES policy design, implementation and context. We use the case for a woodland-for-water payment for ecosystem services (PES) and model its implementation in a local area of Catalonia (NE Spain). Our question of interest is: how do structural and agent-based factors affect the effectiveness of an incentive policy to integrate the forest and water sector? By structural factors, we mean different designs of a PES policy. For agent-based factors, we make use of the literature on landowner behavioral studies about reception and reaction to incentive policies from European-focused studies. By success, we understand that both the ecological but also social goals of the policy are reached in the most effective manner. Our focus in Europe surges from the general context of land abandonment that many Mediterranean areas and Eastern countries are experiencing, and the growing interest from policy-makers and practitioners on the implementation of PES schemes to ameliorate this situation.

2. Entities, state variables, and scales

Agents/individuals. The agents of the model are forest owners with two characteristics: (a) belonging to a collective with behavioral characteristics (see *Collectives* below) and (b) owning a random number of ha of forests with conifers and broadleaf (see *Environment*). The number of owners can be modified by the modeler with an input box. We run the model with 1000 owners, which end up owning ca 50% of the total area and >80% of the forested area –which is close to the amount of km^2 of private ownership for our case study. Whereas the exact number changes every time due to stochastic processes, the average of 100 runs tends to the known amount of private ownership. In the region, Catalonia, there is property atomization by which 95.2% of owners have less than 25 ha (ICEA, 2019). In the county of the area we modelled, la Noguera, there is an estimate of ca. 1800 owners with a third each of >25 ha, 1-25 ha and < 1 ha (Fletas, Bayona, & Cervera, 2012). The model represents this situation, with owners receiving from 1 to 25 ha in random numbers. Forest owners are also allocated a typology based on behavioral studies. This is further explained in the ODD section: sub-models.

Spatial units (e.g., grid cells). The spatial units are type of land, and includes four types of entities: conifers, broadleaf, shrubland (i.e. vegetation cover) and water or agricultural land. Whereas this later fields have no state variable but just represents the geographical area used for the spatially explicit model, the other three change under certain influences. The patches have always the same identity in the initiation but they might go under land conversion or land management processes. With land conversion:

conifers and broadleaf receive a random age and at a certain 'old' age they either turn into shrubland or reproduce leaving a younger tree of the same species. This process is random, with greater chances of conversion than regeneration due to the general context of climate change and drought (Cáceres et al., 2015). They can also be 'managed' by forest owners, by which they are cut and naturally regenerated. Both conifers and broadleaf have a certain water efficiency rate: this can be impoverished due to climate change or improved through regeneration/management. The rate they receive is random following the estimations for this type of trees in the region.

Environment. The environment of the model is characterized by scenarios with and without climate change. Without climate change, there is a certain amount of stable precipitation and rare drought episodes. This is based on climatological data for the area of study. With climate change, the amount of precipitation decreases and droughts occur more often. Droughts produce a certain amount of tree dieback. The climate change projections are based on a climate model for the region (Catalonia), and affect not only precipitation and droughts, but also the rate of water use efficiency of trees.

Collectives. This is the most important *theoretical assumption* in our model, which we could not contrast with actual data for the region, but we base its distribution in expertise knowledge [from the agency responsible for forest private property in the region plus several EU-funded studies conducted there]. Forest owners are allocated in a certain 'collective'. These collectives imply a set of social norms and cultural values and determine the decision model that agents follow. We build the agent's decision model based on theories of forest owner typologies and expected behavioral attributes. We implement four out of the six typologies present in the literature and based on empirical data from European forest owner studies (Sotirov, Sallnäs, & Eriksson, 2017), emulating the situation in our case study. These are (1) environmentalist (do not manage / manage long-term); (2) multi-functionalists (manage short-term / manage long-term); (3) traditionalists (manage short-term / manage long-term) and (4) passives (do not manage). Excluded typologies are (5) optimizers and (6) maximizers –who are generally large-scale forest owners not present in our case study (Fletas et al., 2012).
The management decisions of collectives are based on the characteristics of the policy. The characteristics can be changed in the model interface, and were based on a review of the PES literature. These include: payment frequency, presence of an intermediary, number of ecosystem services and cost coverage. They are all binary. Management starts at model initiation, and it repeats itself depending on the type of policy design in place (short / long term / attrition / none). There is one exception to this rule: traditionalists do not respond to changes in policy design, but follow their direct neighbors.

Spatial and temporal scales. The model landscape consists of an area of 270 km^2. There are 32508.0 pixels and each represents 0.8 ha. One time step represents one year and simulations run for 100 years –in netlogo, until the environment loses its resilience, with forested areas converted into shrubland. The model landscape data is incorporated via the GIS extension. The required document ("mscr_raster.asc") is provided as additional documentation in COMSES or in the Netlogo database.

3. Process overview and scheduling

The first step of the model is loading the map to display the model landscape based on GIS data. This distributes the land cover types representing the territory. At this stage, the observer keeps track of the land cover composition –and will do so until the end of the model. Land cover receives a color based on the tree species, which are grouped in two main categories: conifers and broadleaf. Age is distributed randomly among the later between 20 and 150 or 100 accordingly. Precipitation (global) and water efficiency (individual) is set at the basis. The model simulation currently includes direct distribution of forest owners across the territory when setting up the landscape, but the code can be easily modified to separate the two steps. In this agent distribution, forest owners receive a number of ha distributed jointly across the territory, as well as a forest owner category (collective). At this stage, the modeler needs to decide also on the characteristics of the policy design.

There are three main processes which influence the forest cover once the model is initiated: the decisions of forest owners on managing or not and the type of management ('initiate-management'), the effects of climate change (if activated) on the environmental variables ('change-blue-water', 'experience-drought'), and their own aging ('grow-old'). Management is a discrete variable which manifests at the same time for each forest owner category: it can be short or long term –information which is based on the management recommendations from the forest authority of the region (Piqué, Vericat, & Beltrán, 2017). This happens differently depending on policy design and forest owner, as well as forest type. Drought happens increasingly often the lower the levels of precipitation (lowered by climate change across the years) and produces tree conversion to scrubland in older trees in a random fashion. As forests stands are regenerated, their state variables vary to show base levels that will be again modified through either climate change effects or aging. This means that there is an asynchronous updating of these variables in land cover with forest. One factor our model does not include is seasonality, provided we model the changes in a yearly basis and thus we include only known average data processes.

Note: the code in Netlogo is accompanied by the pseudo-code which was used to build the model.

4. Design concepts

Basic principles. We understand our study as a case of policy integration across the forest and water sectors, and some of the policy integration literature understands it as a complex system (Briassoulis & McDonald, 2005). This implies that every manifestation of policy integration across natural resources will contain the known properties of complex systems. The second argument requiring the model surges from the literature on forest owner behavior in Europe. Generally, scholars have observed policy attrition by which land owners abandon a policy once implemented or do not change their management and reject the policy despite the presence of financial incentives. For this reason, the effects of a policy should incorporate the element of disengagement of the community, moreover in the place of payment for ecosystem services that consist of a voluntary process. Thus, the aim of the study is to observe if policy designs would imply important differences among them –and observe the interplay between these structural factors and agent-based factors such as social norms and values. The hypotheses are, following the literature, that some forest owners will feel aligned with the conservation goals of the policy and act accordingly, but some forest owners will maintain a passive behavior independently of any factor. In a continuum between these two extremes, there will be owners who feel peer-pressure and follow a certain leadership, whilst others might show only partial compliance. Finally, at ecological level, we introduce the estimates of the impact of climate change on forest water use efficiency (WUE) as modelled for the region with the model GOTILWA+ (see input data).

Emergence. The main output of interest is the amount of managed forest. This factor varies depending on the distribution of forest owners typologies. From the typologies, the one with most room for emergency is the typology of traditionalists, who manage following the decision that their neighbors take. In case being surrounded by passive neighbors, low participation in the policy scheme is expected and with it, the water use efficiency gains from the implementation of the PES policy.

Adaptation. The forest owners when they opt for managing their territory they will do so by choosing the most damaged forest stands. The implementation of this adaptive behavior is made through the age as proxy for the condition of a forest. The aim is to optimize the average water efficiency rate, provided the goal of the PES scheme is to change the management to improve water-related ecosystem services among which those of provision.

Objectives. The objectives of the agents are masked by their belonging to a certain typology. These typologies are based on empirical data from studies comparing several European datasets and cluster landowners based on the degree to which they respond to a model of *homo economicus, sociologicus* or *psychologicus* (Deuffic, Sotirov, & Arts, 2018; Sotirov et al., 2017). Each have different affinity to more material-based incentive such as fiduciary to more environmentally driven behaviors (including different management preferences). Thus, this factor is only included indirectly in the model.

Learning. Learning is not specifically modelled in the current version of the model. The only collective that could display signs of learning, nonetheless, is the traditionalists: the more they observe neighbors participating in the PES scheme, the more they would change their own management decisions by changing from passive to active behaviors.

Prediction. The current version of the model does not include prediction. This is one of the weaknesses of behavioral models of forest owners because they are based on the assumption that values are static. Because our model includes the effects of climate change, as well as a long period of time, it is possible that with greater impacts on the region forest owners would change their values and thus adapt decisions on the best management type to meet their values. At the same time, at the ecological level, the risk of forest fires and rendering parts of the landscape degraded due to droughts would also change the possibilities available to landowners and forest authorities (the implied PES financers).

Sensing. One of the forest owner typologies (traditionalists) notices how their neighbors perform: the other typologies are driven by internal cues. In terms of agent-environment, forest owners sense those trees stands that are more damaged (older) and they start managing them rather than younger ones. Costs for cognition and for gathering information are not explicitly included in the model.

Interaction. At model initiation, the territory is distributed across forest owners and they are allocated a certain number of ha. This allocations will not overlap and remain the same, independently of the state of the forest stands. Implicitly, one of the policy design characteristics assumes interaction between the forest authorities and forest owners, with the presence of an intermediary. However, this aspect is not modelled and does only affect the decision to manage of certain owners.

Stochasticity. There are several sources of stochasticity. In order of appearance in the model: the size of owned territory by each forest owner, the age of trees, the frequency and impact of drought –with increases depending on the level of precipitation-, and finally, the level and change in water use efficiency in trees. By the climate models of the region it is known that this level and its modification will not always be of a fixed rate but it will imply a certain percentage. Every time a forest parcel is managed, the forest stands will take a random number within the expected range.

Observation. The data collected from the ABM model is the number of owned and managed ha by forest owner typology, and the evolution of the average water use efficiency rate. This data is collected by types of policy design. There are four main scenarios modelled: one scenario without the presence of the policy, the optimal policy design in which all best practices are activated, the long-term policy design, by which 'close-to-nature' policies with lower frequency of management is activated and finally, the below-cost-coverage policy –by which only multi-functionalists react to the presence of the policy.

5. Initialization

At initialization, the modeler chooses three aspects, related to each of the sub-models.

- For the ecological sub-model, the most important decision is to decide if climate change effects are activated. If activated, the other variables (precipitation and evapotranspiration –ET), will change across the years: the set up points are based on data from the case study.
- For the social sub-model, the user needs to choose the number of forest owners (for the study, established at 1000) and the distribution of forest owner typologies (% of each typology). Number of ha per owner are then randomly distributed. The number of management plans are also

distributed at this stage. The current number reflects the actual known presence of forest management plans from private forest owners.

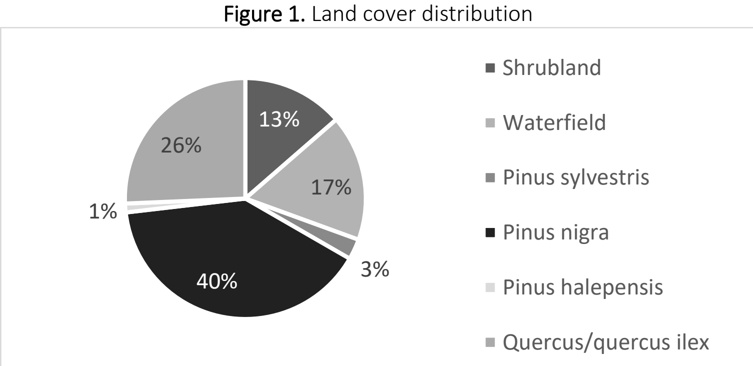
- For the structural sub-model, the modeler chooses the policy design. This will have impacts on the type of management implemented by forest owners depending on their collective belonging. If the first characteristic is activated ('below-cost-coverage?'), this is equal to a scenario without policy and thus just the evolution of the ecosystem without the PES policy in place.

Once these variables are selected and the 'world' is created, the model landscape is always placed identically following GIS data from the area, including distribution of broadleaf and conifers. Trees receive a random age between 20 and 150 years. Forest owners receive also a property between 1 and 30 ha, following the forest ownership distribution of the case study.

The table below displays the base values of these mentioned variables (sources discussed next):

	Data	Base values	Source
Ecological	Average annual precipitation	575 mm/y	Management Plan of Rialb
	Annual change	-0.2%/y	
	ET by species and change		GOTILWA+
	Black pine	65-85%, +5%/150 y	
	Oak	85-92%, +5%/150 y	
	Run-off by species and change		
	Black pine	15-35%, -5%/150 y	
	Oak	8-15%, -5%/150 y	
	Impact of management		
	On blue water, black pine	0-10%	
	On blue water, oak	0-5%	
	Land cover (see Fig.1)	Pinus+ as conifers; Quercus+ as broadleaf	GIS data
	Tree age	Trees receive a (random) age between 20-150/100 years depending on specie.	-
Social	Property type	93% private	Management Plan of Rialb
	Number of owners	1000	
	Number of management plans	10%	
	Number of km^2	280 km^2/350 km^2	
	Typology of forest owner	Behavioural models	(Sotirov et al., 2017)
Structural	Recurrent payments	ST + LT Management with attrition	ORGEST guides Short-term ST: every 15/35 Long-term LT: every 50/100
	Presence of intermediary	ST management / no management	
	N environmental goals	LT management	
	Financial coverage	ST + LT Management / No management	

Figure 1. Land cover distribution



6. Input data

As observed in the table above, there are several data sources mentioned.

- *GIS data*. The GIS is used to implement a spatially-explicit model. It contains data on the type of forest species present in the area as well as their distribution. Fig. 1 shows the land cover.
- *Management plan of Rialb*. The MP of the Rialb area was created by the Foundation 'Territori i paisatge', and it describes the main characteristics of our case study (FTiP, 2003). It was used to obtain average precipitation and the climate change projections affecting it.
- *GOTILWA+.* The model name is an acronym for Growth Of Trees Is Limited by WAter. As the name indicates, this mechanistic deterministic forest growth model combines climate and forest data to simulate forest growth from different management techniques (including management absence) (Gracia, Sabaté, & Sánchez, 2003). We use it in combination with the ORGEST guides as explained next.
- *ORGEST guides*. The ORGEST guides are sustainable and multifunctional forest management guides developed for mixed and pure forest stands of Catalonia (Piqué et al., 2017). They were requested from the Forest Ownership Center (Minister of Agriculture) to support private and public forest management decisions, taking into account the expected effects of climate change in a private area. From these guides, we obtain the number of years suggested to manage a certain forest stand (i.e. pinus nigra, quercus ilex) to improve water use efficiency. Specifically, we use the outputs from an EU-funded project, DEMORGEST, which used the ORGEST guides in combination with GOTILWA+ (Nadal-Sala, Sabaté, Gracia, & CPF, 2014).
- *Workshop*. Two members of our team are from the Forest Ownership Center (CPF) of Catalonia, acting as partners in an EU-funded project studying innovations for forests ecosystems, among which the implementation of Payment for Ecosystem Services (Hz2020 Sincere). The chosen case is Rialb, where we decided to develop the current agent-base model to support the research process about the effects of a PES scheme at the ecological and social systems in the area. The workshop was held with stakeholders, including forest owners and local authorities, and discussed different designs for the PES scheme that would facilitate participation from the community. For more information, see the manuscript accompanying our model.

7. Sub-models

The manuscript accompanying this model presents further information about the interaction between models. Here, we summarize the information and some of the base scenario data of the sub-models.

Ecological sub-model

- *Tree aging*. Every year trees grow older. Older trees are the ones selected for management and also more susceptible to get affected by drought.
- *Climate change*. The effects of climate change are two-fold: on the decrease in annual average precipitation and the higher rate of evapotranspiration from the two forest species (conifers and broadleaf). This later is labelled 'green water'.
    - *Precipitation.* Decreases 1.15 mm per year.
    - *Blue water* (*to change-blue-water).* Blue water is the percentage left of water after the process of evapotranspiration (ET). It is calculated in percentage, and it decreases 0.03 yearly, which implies a lowered water yield.
- *Drought*. Observed that drought is affected by climate change but also by forest structure, with land abandonment processes and its consequent increase in forest mass (forest growth and densification) maintaining similar patterns of drought stress (de Caceres et al., 2015). Main problem of difficult prediction of drought effects on tree decay or mortality (idem).

In the model (*to experience-drought)*, drought is an event experienced by the landscape every 20 years. It affects trees older than 100 years in a rate that changes depending on the levels of precipitation: (a) Over 500 mm/year. A dice is rolled and depending on the number, at 10% chance each, trees turn brown (dieback) or become scrubland; (b) 500-450 mm/year. Same processes, at 20% change; and (c) below 450 mm/year. Same processes, at 25% chance.

Social and policy sub-models

The objective of the policy is to incentivize landowners to change their management. To manage, in the context of our model means thinning the forest every certain shorten periods and cutting followed by natural regeneration. In this later situation, new trees reset age to 20 and reduce the evapotranspiration rate. This later, by a 0-10% (random) for conifers and a 0-5% (random) for broadleaf. Management can imply either both (thinning and cutting) or only thinning, depending on the collective of forest owners.

- Management type (DEMORGEST):
  - Thinning (short-conifer): every 15 years
  - Thinning-broadleaf (short- broadleaf): every 35 years
  - End of rotation (long-conifer): every 50 years
  - End of rotation (long-broadleaf): every 100 years

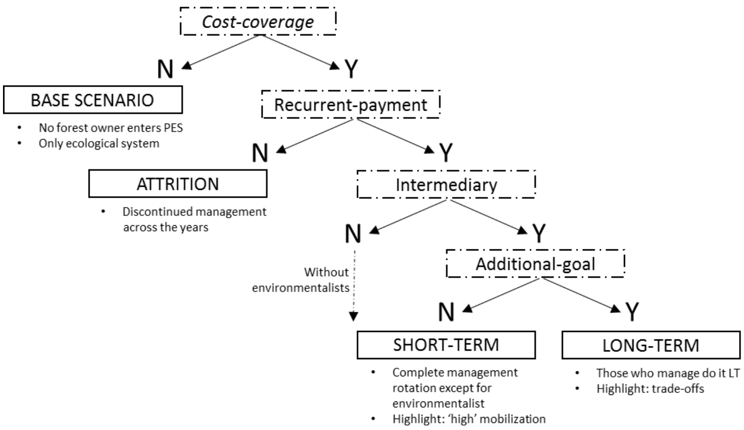
The forest owner typologies interact with the type of policy design which is in place. The two tables below show how each of the categories is expected to proceed following its core values.

Forest owner	**Behavioral models (Sotirov et al., 2017)**	**Implemented in SESPES**
Optimizers (O)	*Intensive profit-oriented even-aged forestry while respecting (minimal) rules*	Absent
Traditionalists (T)	*Low intensive, close-to-nature forestry based on family tradition, local knowledge and sporadic needs*	Triggered by neighbors' behavior, but not by policy design. If neighbors manage, they also initiate manage with thinning and cutting periods.
Maximizers (M)	*Highly intensive (short-rotation) profit-oriented forestry; Sometimes without respecting rules (e.g. "illegal loggers")*	Absent
Passives (P)	*Passive/little management due to lack of interest in forestry according to urban values and life style*	Passives never manage
Multi-functionalists (MF)	*Medium intensive, mixed-objective forestry in respect of professional forestry rules and norms*	Very responsive to policy design. Generally do the complete management (thinning and cutting) unless more than two ES goals are pursued (due to trade-offs).
Environmentalists (E)	*Passive non-intervention and/or extensive forest management due to environmental core beliefs and values*	They are responsive to policy design and if triggered, they will only manage long-term due to values.

Policy design	Explanation
Below-cost-coverage?	*The policy covers (or not) the cost of the change in management required to improve water bodies. If not, the scenario is equal to only the ecosystem submodel.*
One-time-payment?	*Payment can be done regularly or at the end of a management period. Regular payments were shown to maintain landowner participation in the PES scheme. Thus, if one-time payment is activated, it represents a situation of attrition: every certain years (15), the number of owners reduces by 10% each time.*
No-intermediary?	*The figure of an intermediary (e.g. the administration, a coordinating agency, etc.) has been shown to improve PES scheme participation and commitment.*
Additional-ES-goal?	*To pursue more than one goal is detrimental provided the different management requirements it can imply.*

The below figure maps the type of policy and the response expected from forest owners:

Figure 2. Type of policy design and behavioral responses: opted-for scenarios



8. Additional: possible extensions

The first extension could include the introduction of private service users –who benefit from the provision of ecosystem services and would finance service providers. Currently, the model assumes it is a government-financed PES (Sven Wunder, 2015). An additional extension involving the type of management would be to reduce the forest mass. This could be implemented by modelling areas with certain risk, and reducing the size of the patches to represent less ha. Finally, another extension of the model could include the perception of forest fire risk in the current spatially explicit model. This could let forest owners estimate future consequences of their decisions.

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