Agent Based Modelling for Climate Smart Landscape – Design document

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Contents

Abstract:

Description

This document designs an Agent Based Modelling development for Climate-Smart Landscapes (CSL).
The aim is to implement a conceptual socio-environmental system modelling using an agent-based approach (see introduction).

Significance

We have developed the design of a socio-environmental system modelling using an agent-based approach under Climate-Smart Landscape context. This conceptual model fits the NZ environment and is flexible to incorporate real or virtual ladscapes. Agents represents the environmental units to take into account climate change scenarios and real land managers (farmers, landowners) to simulate decision-making process incentivised by several decision levels.

This conceptual work will allow to develop the agent-based model from next FY, and start exploring scenarios and design pathways.

1. Introduction

Context and aim of ABM4CSL.

ABM4CSL is the Agent Based Model for Climate-Smart Landscapes plan. This document designs the framework of such an ABM development.

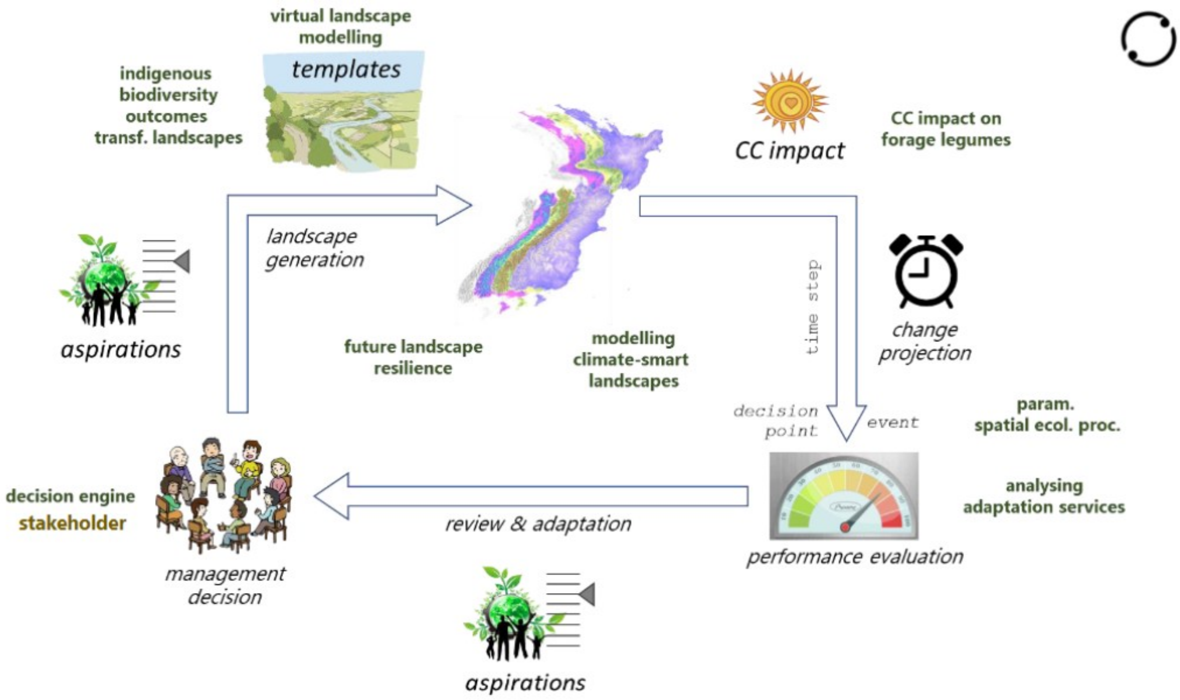

Figure 1- Climate-Smart Landscapes modelling strategy.

The aim of this work is to implement a conceptual socio-environmental system modelling using an agent-based approach. This model is embedded in the CSL modelling strategy (Figure 1) under the decision engine/stakeholder/management decision corner.

The model objective is to achieve healthy landscapes and community under Climate-Smart Landscapes by maximising Ecosystem Services (ES) performances (single or multi-ES), land sustainability and resilience, community well-being, profitability of the land and activities. Several pathways should be able to achieve this multi-objective goals. Those pathways are a different combination of the land, stakeholders, landowners, management practices, public policy, etc. But what best combinations drive best results? This agent-based model should reply to this question by quantifying/qualifying the following elements:

- Who shapes the landscape? By what sort of decision?
- At what scales are made decisions? and what scale is the most impactful?
- What are the impacts of actions for provision of Ecosystem Services (ES)?
- What are the best combinations to achieve CSL/Healthy landscapes?

Elements from the literature

This subsection is in progress

Several ABM examples have been reviewed, mainly ABM examples applied to agricultural areas or environmental or policy issues; or behavioural analysis for modelling purposes in the agricultural and forestry sector. This helped shape the general ideas and general design of ABM4CSL.

(Villamor et al., 2022) Their review concludes the representation of adaptation behaviour and decision-making remain very limited in most of the ABM in the forestry sector.

(Brown et al., 2016) analysed the Rural decision maker survey 2013. Regional councils are not trusted by the rural decision makers for following incentives. Innovators and connectors are young, males, highly educated, financially robust operators on any sort of farm. Education level and financial robustness are the two main characteristics of trust in environmental performance information.

(Brown and Roper, 2017) to reach government objectives (sustainability AND profitability), farmers are expected to adopt pro-environmental management practices and novel farm technologies. They are more likely to adopt new practices and technologies after seeing them demonstrated, but earlier evidence indicates that demonstration is most effectively undertaken within farmer networks (not council or regional incentives).

(Bartkowski et al., 2020) aligns multi-objectives land use allocation and ABM using Pareto front optimisation techniques. Need to be developed on real landscapes with more LU options (at the moment: virtual landscapes of 15*15 pixels, 2 LU types + a river, 3 ES computed, basic economics).

(Morgan and Daigneault, 2015) developed an economic based ABM. Results are highly predictable as the economic environment drives the decision making of agents. In this example, Dairy production is always more profitable than any other option, and it is leaching more than any other option. With governmental incentives to reduce GHG emissions, it is predictable Dairy production will increase, as well as forestry to offset emissions, at the expense of B&S (as there is no other option in the model).

→ ABM with static agents is similar to systems dynamic approach. They both allow for retroactions and feedback loops. ABM allow also for spatial approach, combining raster/GIS matrix spatial approach and aspatial parameters hold by agents. However, the agent components are not fundamental as the decision-making follow logical rules.

(Yletyinen et al., 2021) explored the capacity of social influence to generate environmental outcomes. Based on national-scale survey data and a social-ecological system, the agent-based model is applied in the context of voluntary private land conservation. The model structure is very interesting and close to the main framework of the ABM4CSL model expectation. The model consists of (A) three cross-scale actor groups and their influence links to landowners; (B) 200 heterogeneous landowners, each with his or her actor attributes, and influence links between landowners (peer influence); (C) a simulated agricultural landscape with areas available for conservation on each farm, upon which the landowner makes conservation decisions (dashed line); (D) a binary ecological landscape emerging from conservation action and consisting of either protected or unprotected land, coloured here accordingly; (E) spatial diffusion knowledge to each landowner from his or her neighbouring farms (here illustrated with one arrow only).

- ➔ In this example, the authors analyse especially the interactions in the decision making process (social part of the modelling) but not the environmental part as much. Changes in Land Use are only taken into account as a result of the social process and doesn’t add any sort of complexity in the decision process. The land is a basic binary option of possible conservation or not (whatever the land use, and predetermined by the authors).
- ➔ The social part of the model is very close to what we expect to develop for ABM4CSL. However, the landscape and environmental part will be much more complex and will take part in the decision process of agents.

(Caillault et al., 2013) have developed a similar model to evaluate the impact of different incentive network on the landscape change. The three incentives tested are close to what we aim to develop. The scale of this example is interesting as it is relevant to landscape scales. The approach to analyse the effect of single and multiple incentives on the landscape patterns is very relevant to future development (some incentives being spatial like the neighbourhood, some not, like the agent behaviour to follow gov incentives or not).

(Tissot et al., 2020) have developed an ABM to reproduce real behaviours of viticulture farmers in the context of climate change adaptation. Authors have developed a very strong environmental system taking into account the vine species and adaptation capacity, yields, growth, soils, past current and future climate conditions under 4 IPCC scenarios. The farmers behaviours are adapting to evolutive situations (pathogens, practices). The objective of this model is to design pathways of adaptation for farmers. It is a very local application with very precise modelling that can’t be extrapolated at the landscape or regional level.

- ➔ This degree of precision is too high for the land/practices/environment to be applied at the scale of interest for CSL.
- ➔ This work is developed for prediction and pathway design, in close relationship with farmers. It is not suitable for scenario testing (the only scenarios here are IPCC scenarios).

(Yuan et al., 2014) This study integrates a multiagent system (MAS) that simulates the behaviours of land-use stakeholders with regard to their choices of specific locations, with a genetic algorithm (GA) that simultaneously evaluates and optimizes land-use configurations to meet various regional development objectives. Multi-objective optimization problem is solved using Pareto-front-based method and weighted sum methods. ABM platform is not specified. Not sure why coupling both methods lead to better optimisation of the land use.

(Whittaker et al., 2017) designed an integrated solution using hybrid genetic algorithm applied to agri-environmental policy optimisation at 2 different scales (gov agency and stakeholders). It is an example of ABM and optimisation process run at the same time, also coupling a biophysical model SWAT. The optimisation algorithm found multiple different policy configurations that achieved nearly identical results for the upper level (agency) objectives.

(Brunner et al., 2016) simulated the supply of ES using economic agent-based land-use model ALUAM-AB (Alpine Land Use Allocation Model – Agent Based) using Linear Programming Language and a CPLEX solver. The model is setup and parametrised for the study site only. Backcasting approach for Brunner et al., 2016 and Haslauer et al., 2016 to design trajectories.

(Kim et al., 2018) developed a two-phase simulation-based framework for finding the optimal locations of biomass storage facilities. They used AnyLogic® as ABM software and optimisation engine. Need to investigate this platform. Also need to investigate location/allocation GIS model for LU optimisation.

Synthesis and plan

From those examples, several aspects appear fundamental for ABM4CSL development:

- Landscape to catchment to regional scale model
- Variety of agents and behaviours to represent the diversity of the real world
- Various scales of incentives, spatial and aspatial
- Diversity of land use and land practices
- Different environmental analysis
- Sub-models for systems complexity representation

Development and analysis should gradually add complexity to understand the land use change and decision-making processes, and then design pathways to adaptation and resilience.

Strengths of this model development are:

- The design allows for general research question testing (virtual landscape option) as well as real landscape upload (not parametrised for one study site only).
- Open access code and online platform for scenario design.

- The flexibility of the structure allowing for submodels to be added/tested or not selected.
- The wide variety of submodels/disruptors to be added and tested one by one or together.

In this document, we characterise key elements of an ABM (i.e. agents such as natural entities, farmers, stakeholders, sectors, industries, regions/government) and conceptualise a multi-scale/multi-level system. This model should allow for testing of several parameters combination (e.g., agent behaviours at different scales, disruptions in the landscape system, initial landscape, and land use management) using a range of evaluation indicators (e.g., single, and multi-ES performances, profitability, sustainability).

The document is organised in four main parts and includes all necessary elements for a future ABM development:

- Agent types and behaviours
- Landscape, scales and levels of decisions and actions
- Process: interactions between agents and landscape (submodel systems/organisation)
- Experimentation plan

2. Agent types and behaviours

Three different agent types, i.e. human, biophysical and entity agents, and several external factors are defined for active decision making and land management (Figure 2).

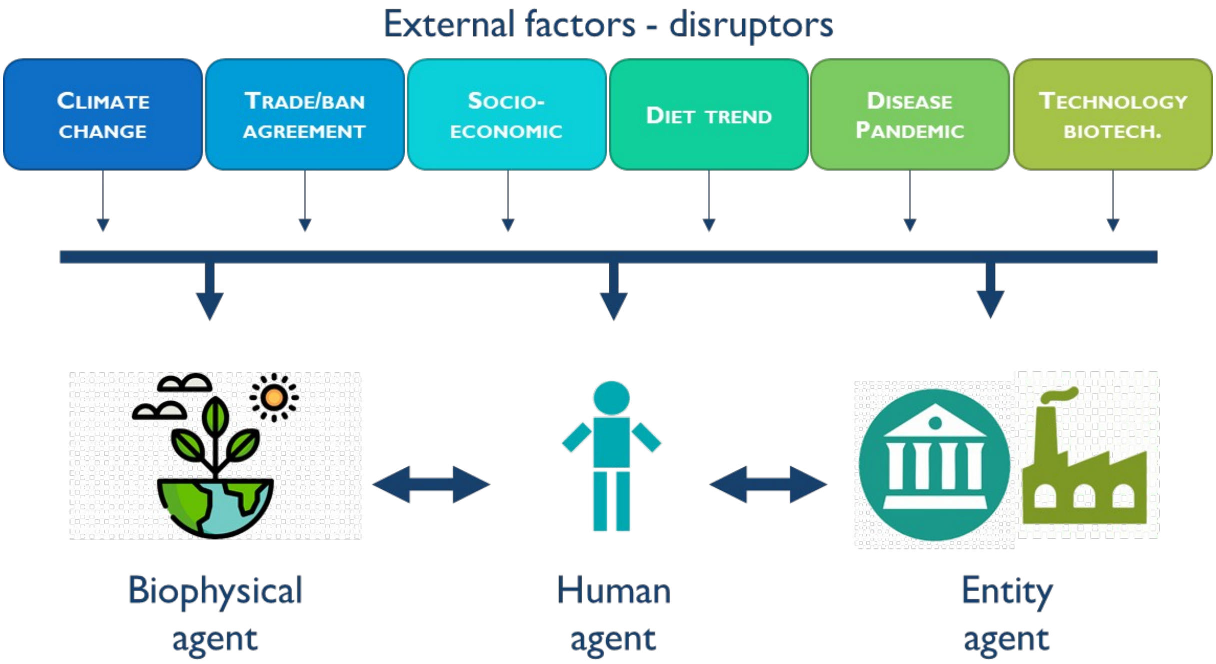

Figure 2 – Agent types and basic interactions.

Human agent is central to decision making and land management and react to different levels of information and incentives. Biophysical agents communicate information on growing and living condition to the human agent for management. Entity agents send incentives to human agent (new law, opportunity, options) for obligation to comply or management change. External factors play the role of disruptors along the time for agents to adapt to new situations.

2.1. Biophysical agents

They are homogeneous units, like parcels or plots, with any type of land cover. Those units are defined by a soil type, a topography, a climate, a cover, and a management/use.

The units are possibly represented in a GIS layer, or a cell under matrix/virtual landscapes. The size of the unit varies according to the homogeneity of the attributes in a GIS layer; or is fixed for matrix landscapes (raster files).

2.2. Human agents

There are 5 subtypes of human agents: growers, livestock farmers, foresters, tourism landowners, lifestyle block owners. Human agent types are linked to a land use/cover type (see section 3.1.).

Human agents have a behaviour category defined at the setup (Table 1). Their behaviour drives their choices over the time. Depending on the human agent function (farmer, forester, landowner, etc), choices are different even under the same behaviour type because land use and functions are different. For example, a Livestock farmer with a climate conscious behaviour will not take the same actions than a tourism landowner with climate conscious behaviour. However, they will both make positive choices on mitigating and adapting to climate change regarding their own situation.

The table 1 describes the main behaviour characteristics for the different agent type and behaviour types. This table is largely inspired from the results of the Survey of Rural Decision Makers 2021.

Table 1 could be completed, work in progress.

<table>
<tr><td colspan="2"></td><td colspan="8">Behaviour type</td></tr>
<tr><td colspan="2" rowspan="2">Human agent type</td><td colspan="2">Business as usual</td><td colspan="2">Profit maximisation</td><td colspan="2">Climate conscious (passive - follower)</td><td colspan="2">Climate conscious (active)</td></tr>
<tr><td>Description</td><td>Assumption</td><td>Description</td><td>Assumption</td><td>Description</td><td>Assumption</td><td>Description</td><td>Assumption</td></tr>
<tr><td colspan="2">All human agents</td><td>Keep going, impact of CC or other disruptors will be balanced on my operation anyway.</td><td>Agent decides by himself and comply with Law.
No disruptive change on the way the agent is operating.
Mitigation is an option if necessary.</td><td>Keep growing, I have strong optimism for the future of my $ benefits and performances</td><td>Agent decides according to industry incentives first. Choices are guided by economic profit alone, according to the best possibilities of the plot.</td><td>Let’s think! Impact of climate change can be some years negative, some years positive.
Mitigating looks a good option as long as benefits and costs are well known.</td><td>Agent decides by himself and following his social connections/peers/neighbours. Comply with Law and follow regional/local incentives.
Choose easily to mitigate with well-known processes.
Follow others on new practices and tech implementation.
Follow also active climate conscious agent when they are neighbours and don’t take too many risks.</td><td>Engage the change, adapt, and give back to the land and community. These agents are the most inventive and take risks for adaptation.</td><td>Mitigation is not enough, and adaptation of the farming/tourism systems is required. Strong choices to high tech or RegenAg are taken without option to go back.</td></tr>
<tr><td colspan="10">Application examples per agent type</td></tr>
<tr><td rowspan="2">Grower</td><td>Perennial (horticulture)</td><td colspan="2" rowspan="2">• Arable and perennial are low but slowly growing, yield increased, high value production
• Irrigation and fertiliser use are mainstream (high)</td><td colspan="2">• New high value productions are available due to cc (new or existing shifts)
• Monoproduction on large areas of high value fruits for exportation</td><td colspan="2" rowspan="2">• Reduce high water demand irrigation system
• increase efficient irrigation systems
• Soil moisture sensors investment
• Precision ag</td><td colspan="2">• No more irrigation or very limited
• Develop RegenAg/organic farming principles
• Agroforestry
• Mixed farming instead of monocropping</td></tr>
<tr><td>Arable (annual cropping)</td><td colspan="2">• New high value productions are available due to cc (new or existing shifts)
• Monocropping is best value possible.
• Any tech/biotech improving yield is used</td><td colspan="2">• Develop RegenAg/organic farming principles
• Mixed farming instead of monocropping
• Crop type adaptation to climate/soil
• Very limited irrigation</td></tr>
<tr><td>Livestock farmer</td><td>Dairy</td><td colspan="2">• Dairy area, value, yields are increasing
• animal number slightly decrease</td><td colspan="2">• Dairy area, animal numbers, value, yields are increasing</td><td colspan="2">• Easy technology adoption
• Feed stock low-N (more arable farming on dairy land)
• Manage fertiliser use
• Manage effluent storage
• Restrict stock from waterways
• Decrease in herd number by MPI recommended 15%
• Sustainable use of water and fertilisers</td><td colspan="2">• Develop RegenAg/organic farming principles
• Mixed farming instead of monocropping
• Introduce arable into the dairy system for feed and catch crop in winter
• No more pasture irrigation
• Limiting grazing period combined with housing cattle (McDowell et al.,</td></tr>
</table>

					2022) • Herd number decrease +++
	Sheep &Beef	• Meat production is decreasing (in area and animal number), yields are increasing to keep the sector profitable	• New markets lead to more production	• Easy technology adoption • Feed stock low-N (more arable farming on dairy land) • Plant trees on slopes • Restrict stock from waterways • Couple with arable protein production	• Develop RegenAg/organic farming principles • Agroforestry • Mixed farming instead of monocropping • Share good land with arable farming • Couple with arable protein production, development of new protein products (peas, lentils, new industry)
	Other (Deer, grazin g)	• Deer production is decreasing in animal numbers. Grazing for dairy is increasing.	• Deer production is decreasing in animal numbers. Grazing for dairy is increasing.	• Plant trees on slopes • Restrict stock from waterways • Decrease in herd number by MPI recommended 15% • Sustainable use of water and fertilisers	• Develop RegenAg/organic farming principles • Agroforestry • Mixed farming instead of monocropping
Forester		• Plant and manage to BAU wood production	• Plant and manage to wood prod + create carbon credit for others.	• Adjust harvest level to changing growing conditions • Reduction of rotation period	• No more trees cut (Norway example?) • Native planting and regeneration experiences on farm and off farm
Tourism landowner		• Tourism is developing and extending the range of opportunities in all landscapes.	• Development of any profitable activity possible on any type of land. Water/mountains are the most profitable. • New tourism spot and infrastructure (even high GHG emission). • Changing operation to peri-urban expansion if profitable.	• Native bush planting along waterways • Wetland and habitat protection	• Native bush planting • Wetland restoration or protection • Habitat restoration • Stop of high emission activities, switch to ecotourism only.
Lifestyle block owner		• With high market values, parts of the blocks are sold for periurbanisation.	• Follow market/industry incentives, can sell the whole block for periurbanisation.	• Native bush planting along waterways • Wetland and habitat protection	• Native bush planting • Wetland restoration • Bee keeping • Productive backyard, regenerative/organic.

Table 1 – Behaviours and land cover/use decision description for human agents. (For specific forestry behaviours, disruption and adaptation, see (Villamor et al., 2022).

2.3. Entity agents

Four levels of entities are defined at agent's higher scales (Figure 3):

- Neighbours, peers, and social connections
- Local and regional councils
- Industry sectors (e.g. Dairy NZ, Fonterra, Beef&Lamb, FAR, Zespri, AgriTechNZ)
- Government ministry

Figure 3 – Entity agent organisation and scales.

Each entity agent has his own objectives:

- Neighbours, peers and social connexions will influence the human agent to have the same behaviour (mimic);
- local and regional councils are managing the environmental parameters by fixing limits on irrigation water used, nitrogen and methane emissions, carbon stock in tree planting, environmental health/ES performance levels;
- industry objective is to be economically profitable; it incentivises the human agents by being more profitable regardless of environmental impact;
- government and ministry entity create laws in response to the environmental and economic health (balance) that are repercussed at the regional/local entity level.

Each human agents have a dedicated behaviour that will guide him to follow to a certain degree the instructions from entity agents. For example, some agents will follow their peers as defined by their behaviour, others will first choose to follow industry incentives.

2.4. External factors and agents

External factors play the role of outside disruptors (i.e., climate change, trade agreement/ban, socio-economic, diet trend, disease/pandemic, technology, and biotechnology). They are not represented as agent within the model but provide a direct input/incentive/disruption on one, two or the three types of agents (Figure 4). For example, the climate change will affect all three agent types by a loss of land suitability for a given production, affecting the farmer in profitability and sustainability and more globally the government /industry in the case of an extreme event or a recurrence of extreme events. Change of diet trend will affect only the entity agents (industry) that will incentivise the farmers to adapt his production to keep profits high.

External factors may be implemented as more or less complex sub-models (see section 4.2), climate change and socio-economic being potentially the more complex.

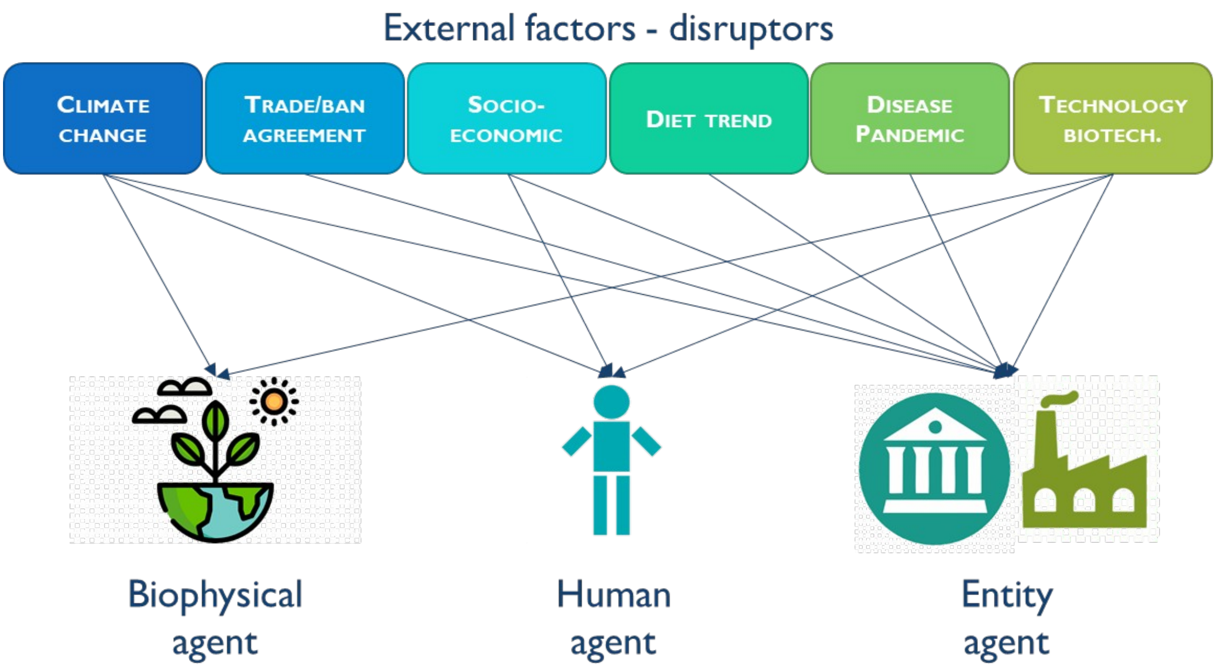

Figure 4 – Disruptor impacts on biophysical, human and entity agents.

3. Landscape, scales and levels of decisions and actions

Land is owned by human agents. Decision of land management or land use change is made by the human agent owning the block.

3.1. Land cover and land use representation

Land is represented as a spatial mapping (raster cells or polygon shapes) of land use or land cover in the simulation interface. The LCDB database covers the land types of interest in 7 or 12 classes (Table 2).

#team discussion should allow for a final definition of the land use classes necessary for running simulations#

Table 2 – Land use correspondence (simple or complex) from LCDB, and agent type and use associated in the model.

Land use (complex)	**LCDB head classes (n=7)**	**Agent use**	**Agent type**	**ES model reclass (simple)**
Artificial	Artificial surface	City and periurban	Lifestyle block owner	-
Open water	Water body	Lake, beach, recreation	all	water
River		River, recreation	all	
Wetland		Wetland, restoration	all	
Crop annual	Cropland	Arable production	Grower (arable)	crops
Crop perennial		Horticultural production	Grower (perennial)	
Grassland (high prod)	Grassland	Dairy, Deer and grazing production	Livestock farmer (dairy, other)	Intensive grass
Grassland (low prod)		Beef and lamb production	Livestock farmer (sheep and beef)	Extensive grass
Lightly vegetated (grass/bare soils)	Bare or lightly vegetated surface	Unproductive land, restoration, protection, recreation.	All	-
Scrub and shrub	Scrub and shrubland	Unproductive land, restoration, protection, recreation	All	Scrub
Native forest	Forest	Unproductive land, protection, recreation	All	Natural forest
Exotic forest		Wood production, recreation	Forester	Exotic forest

3.2. Virtual vs realistic landscapes

In agent-based modelling, agents can interact between them and with their environment. In this model, human agents own pieces of land, and interact with the land to make choices/decision for their piece of land (either to change or not their use/cover or management style).

In the model the land can be represented in two different ways: using virtual landscapes (cell matrix) or realistic landscapes (GIS shape). A virtual landscape in ABM is a grid of pixels where each pixel has biophysical attributes and a human agent owner. Cells are squares of fixed size (#to be determine#) and start with a given land use (random spatial repartition for example). Some land use can't be changed over the time, i.e., open water, river, artificial surfaces, lightly vegetated/bare soils, but their management can evolve over the time (changing for restoration area or tourism site for example). The same principles apply for realistic landscapes, except the size of a unit and its land use is given by the GIS layer at the polygon scale.

In ABM4CSL, two different types of virtual landscapes could be tested, random land use simulations with user defined land use %, and virtual landscapes from Dan Richards/Tom Etherington work (data access already provided by Tom and Dan).

3.3. Land indicators

A list of 16 land indicators (Table 3), including ecosystem services, landscape patterns characterisation, productivity, and profitability index, are proposed to evaluate the overall landscape health. The objective of the model is to find configurations to improve those indicators and find an acceptable balance between ES performance, land profitability and various socio-economic parameters. Land indicators allow to quantify and discuss different pathways within the team, with decision makers, stakeholders, and will help test strategies for CSL templates definition.

3.4. Levels of decision and actions

There are several levels of decision within the ABM, described in the figure 5. Even if each piece of land is owned and managed by a unique human agent, multiple agents/scales/factors are interacting with the human agent before he makes a decision (Figure 3, section 2.3.). Then, the land use changes over the simulation time and modifies the landscape (Figure 5 – emergence). Those changes affect positively or negatively landscape patterns and ecosystem services performances. Indicators, like ES/landscape performances, communicate with entity agents by feedback loops to incentivise human agents. Emergence allow to quantify and characterise changes; feedback loops inform entity agents of the good health/level of performance of the environment.

Landscape performance indicators are described in the section 4.2., table 3.

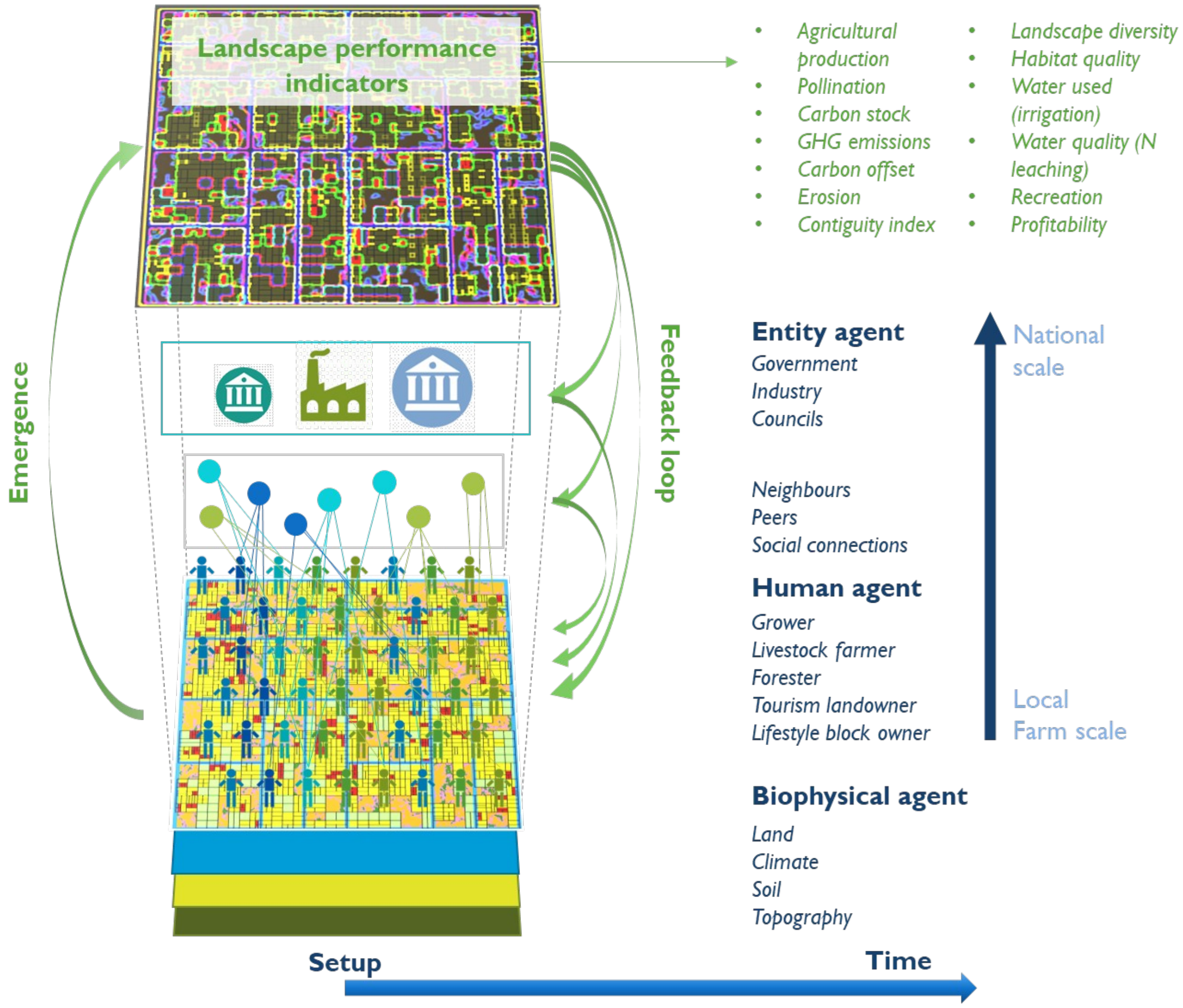

Figure 5 – Multi-level model organisation

4. Process: interactions between agents and landscape

In this section, we describe how agents, and the land are interacting within the model process and what are the process and setup details (input data, sub-models, setup parameters, activity diagram).

4.1. Input data

Agents

Human agent behaviour %:

- User defined for threshold testing purposes,
- Or data analysis from survey (Rural Decision Makers Survey)

Decision level:

Each decision level can be activated/inactivated to test decision levels implication in landscape patterns emergence. This does not require any input data. The active/inactive choice is user defined.

Land

Land use %:

- User defined for virtual landscapes (or uploaded from previous LV work)
- GIS layer from LCDB/LUM
- Any other GIS layer coded along the defined legend for indicators computation

Sub-models

The only spatialised sub-model is the climate. Data from NIWA (https://ofcnz.niwa.co.nz/#/home) related to current and future climate conditions (TC, Pmm, droughts, water yields) could be directly implemented or analysed to implement climate patterns at the biophysical agent level (Tissot et al., 2020).

4.2. Sub-models description

External factors/disruptors sub-models

- Climate

This sub-model is based on the analysis of climate projections by 2050 and 2100 by NIWA. Implementation of:

- The evolution of agricultural growth conditions over the time according to 4 different RCPs (2.6, 4.5, 6.0, 8.6)
- droughts and extreme event patterns (that affect land activities).

User choose between 4 different climate projections.

- Trade/ban agreement

This sub-model run a constant growth of trade agreement for Livestock/Horticultural sector productions (BAU). Industry is confident to produce incentives for more Livestock/Horti production. During the simulation, the sub-model causes random number of disruption in the economics. It simulates a decrease of trade agreement (Dairy/Horti). This could lead to land use change or land abandonment to lifestyle block/periurb.

- Socio-economic

Need to implement a gross value of each type of production (or reuse the export value dataset from previous model). The sub-model could simulate a decrease in the export value and economic shocks leading to land use change or land abandonment.

- Diet trend

Implementation of new global food trend reducing livestock products (dairy, meat) and replacing by arable protein production. Land translation is a switch from dairy/beef/lamb best lands (irrigated) to annual crop production.

- Disease/pandemic

Implementation of a brutal stop of tourism, exports, imports disrupting one or all sectors. Sub-model will affect the land production of several sectors (random choice between 1 and 4) and selected land will switch to other productions or abandonment depending on soil conditions).

- Technology biotech

Implementation of different types of tech improvement for mitigation (reduce of N_2O use and emissions, reduce of CH_4 emissions, CO_2 emissions, increase yields, reduce amount of water used for irrigation). Sub-model is affecting randomly one to five options to human agents with a transition period of about 5-10 years.

ES models and performance indicators

A wide list of indicators is computed at the end of each time step of a simulation. This allows to follow the simulation performances on the land. The Table 3 displays the list of indicators and methods/refs to compute them.

Table 3 – Output indicators for land performances evaluation along the simulation process.

Output indicator	method	reference
Agricultural production (crops)	Proxy (land area*yield)	(Vannier et al., 2022)
Agricultural production (livestock)	Proxy (land area*yield)	(Vannier et al., 2022)
Pollination	Land cover capacity to provide habitat for pollinators, and crop requirement for pollination	Dan Richards et al.
Carbon stock	look-up table relating the land cover type of each pixel to an estimated value of carbon stocks	Dan Richards et al.
GHG emissions (N2O)	nitrogen fertiliser used per agricultural sector (kg/ha/year), CO2eq N2O is carbon dioxide emissions equivalent from nitrogen (tonnes).	(Vannier et al., 2022)
GHG emissions (CO2)	fossil energy used, the total agricultural area and production, CO2eq E is carbon dioxide emissions equivalent from energy used (terajoule/year)	(Vannier et al., 2022)
GHG emissions (CH4)	enteric fermentation and manure management per animal type (kg/CH4/animal/year), CO2eq CH4 is carbon dioxide emissions equivalent from methane (tonnes),	(Vannier et al., 2022)
Carbon offset	Look-up table of Carbon stock by new plantations (native or exotic). Total offset value (in CO2eq) is subtracted from the total emissions (fossil energy used, nitrogen, and methane emissions).	(Vannier et al., 2022)
Erosion	Derivation of the Universal Soil Loss Equation model for New Zealand, which estimates the mean annual erosion rate due to surficial processes	Dan Richards et al.
Contiguity index	Overall continuity value	(McGarigal et al., 2012)
Landscape diversity	Patch diversity index or Shannon index	(McGarigal et al., 2012)
Habitat quality	Bird habitat suitability models a simple relative habitat suitability for two NZ indigenous bird species of significant conservation interest (Kiwi, Kereru).	Dan Richards et al.
Water used (irrigation)	total amount of water used by irrigation per land use type	(Vannier et al., 2022)
Water quality (N	tbd	McDowell et al.

leaching)		
Recreation	relative landscape attractiveness using a recreation opportunity spectrum approach	Dan Richards et al.
Profitability	Proxy (Agricultural prod crops* price + livestock*price)	(Vannier et al., 2022)

4.3. Setup parameters

The model interface is divided in three main parts (Figure 6): setup, simulation, output indicators. The setup parameters are determined before the beginning of a simulation, whereas simulation panel and output indicators are updated for each time-step of a simulation.

Setup parameters cover all the input data, user choices and scenario simulation parameters to determine before running a simulation, i.e., the land use, human agent behaviours, decision levels involved, sub models activation.

Land use is setup at the beginning of each simulation either virtually or using a GIS layer. In virtual landscapes, the user setup the desired % of each land use and the model generates the landscape accordingly. For GIS landscapes, the model computes each land use percentages according to the GIS layer uploaded.

Human agent behaviour % are user defined. Default setup is 25% for each.

Decision levels are activated or inactivated by user depending on the number of interactions levels/decision making complexity desired.

Sub-models are activated or inactivated by user depending on the disruptions desired to test.

- Climate: Users choose between 4 different climate projections.
- Trade: when activated, this sub-model will cause disruption in the economics randomly during the simulation.
- Diet: when activated, this sub-model implements a global/national diet trend change (reduction of meat consumption at the expense of annual/perennial crops).
- Disease/pandemic: when activated, this sub-model will cause disruption in the economics/tourism randomly during the simulation.
- Technology/Biotechnology: when activated, this sub-model will improve in 5-10 years all yields and reduce GHG emissions and/or Nleaching by a set %.

Output indicators are displayed in graphs to follow their value over the time.

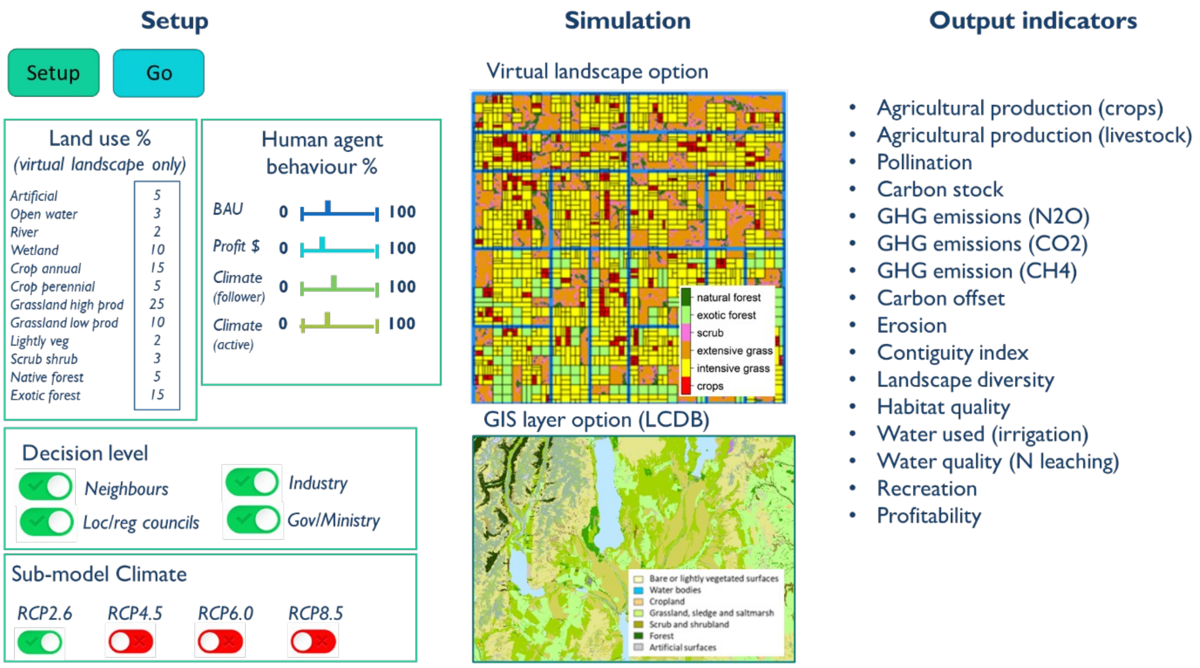

Figure 6 – Model interface example

4.4. Activity diagram

During the simulation, each time step is organised in three main sequences, 1- analyse the state of the land by agents (biophysical, human, entities), 2- take a decision (by combining all information and choosing the more appropriate), 3- compute output performances (Figure 7).

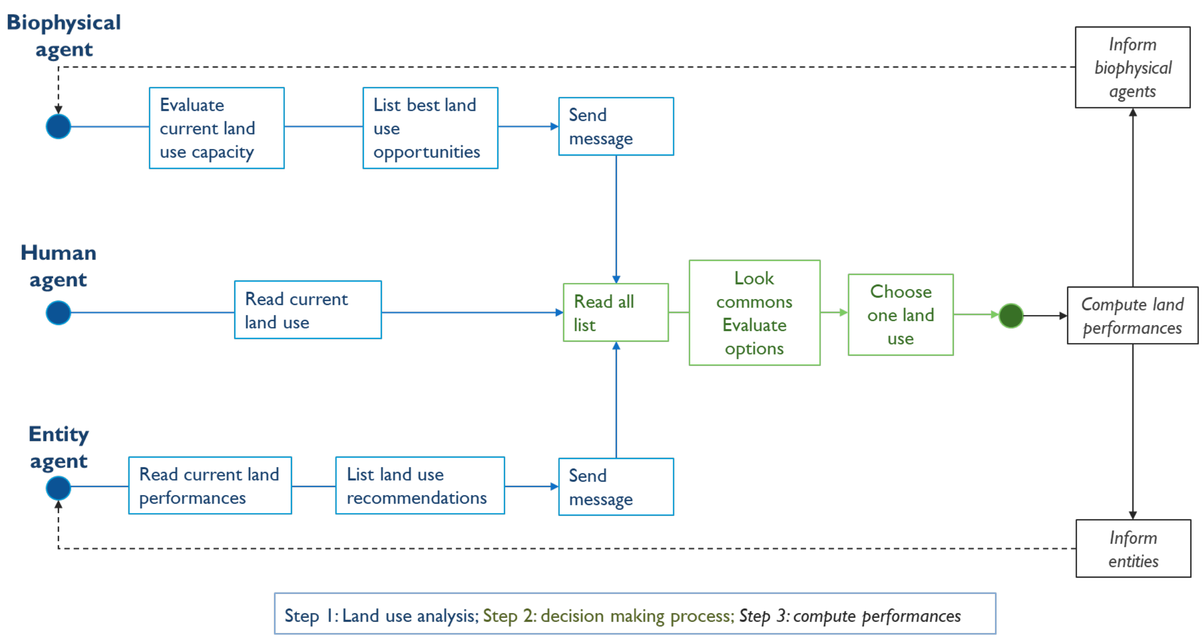

Figure 7 – Activity diagram from agents to land use decision and landscape evaluation.

The critical sequence is the decision making. A decision is always taken by the human agent evaluating the current state from his land, the biophysical agent message of his land, and the entity agents involved. The human agent read all the lists/messages sent by the biophysical and entity agents and evaluate options. His options depend on decision rules (Table 4): 1- the human agent type (farmer, landowner, etc.), 2- the human agent behaviour, 3- the initial land use (land is in place for a given number of time steps, farmer can't change the type of farming each time steps), 4- the entity recommendations.

Even if some land use changes are similar from one behaviour to another, the trends can be quicker/slower, and the practices can differ. It will not be visible on the land interface, but will be taken into account when computing the landscape performances. Values of good practices for Climate Conscious active agents will be better than the similar Climate Conscious passive agents. Same, values of BAU practices from BAU agents can score differently than the same LU but different practice of the Economic Profit agent.

Table 4 – Decision rule details: from human agent type to land use options and choices (where agent behaviours are: Business as Usual -BAU-, Economic profit -EcoP-, Climate Conscious passive -CCP-, Climate conscious active -CCA-).

Human agent type	Land use initial	Land use possibilities	Minimum time set	Limits/ Incentives to grow	Possible switch	Behaviour			
						BAU	EcoP	CCP	CCA
Grower (G)	• Annual crops • Perennial crops	• Annual crops • Perennial crops • Grasslands (high prod)	5 15	Climate Diet trend	G → LF G → Abandonment, native regrowth.	Annual crops stable Perennial crops increase	Monocropping increase Perennial increase	Arable increase Perennial increase	Crop diversification Perennial increase
Livestock farmer (LF)	• Grassland (high prod) • Grassland (low prod)	• Grassland (high prod) • Grassland (low prod) • Arable crops • Exotic forest • Native forest	5 15 5 30 Forever	Climate Diet trend Trade Technology	LF → G LF → Fo LF → Abandonment, native regrowth.	Dairy increase B&L decrease, plant exotic forest for $	Dairy increase++ B&L decrease, plant exotic forest for $	Dairy coupling with arable B&L decrease and plant forest	Arable in livestock systems Forest (exotic&native) planting Dairy decrease
Forester (Fo)	• Exotic forest	• Exotic forest • Grassland (low prod)	30 15	Trade	Fo → LF Fo → Abandonment, native regrowth.	Increase	Carbon storage $ development++	Carbon storage $ development	Carbon + Native
Tourism landowner (TL)	• Water body • Exotic forest • Native forest • Grassland (low prod) • Scrub/shrub	• Water body • Exotic forest • Native forest • Grassland (low prod) • Scrub/shrub • artificial	Forever 30 Forever 15 Forever Forever	Pandemic Socio-economic	TL → LF TL → G TL → Fo TL → urban Abandonment, native regrowth.	Increase	Increase	Stable + land conservation	Native + land conservation Biodiv++
Lifestyle block owner (LBO)	• Water body • Exotic forest • Native forest • Grassland (low prod) • Scrub/shrub	• Water body • Exotic forest • Native forest • Grassland (low prod) • Scrub/shrub • artificial	Forever 30 Forever 15 Forever Forever	Socio-economic	LBO → G LBO → LF LBO → Fo LBO → urban LBO → Abandonment, native regrowth.	Urbanisation	Urbanisation	Plant native, bush, perennials	Plant native, bush, perennials Biodiv++

5. Experimentation plan

Two types of experimentations will be conducted: model sensitivity analysis (land use proportions and human agent behaviour) and scenarios for evaluating the influence of decision levels on landscape performances. Table 5 and 6 display the experimentation plan for the sensitivity analysis and the scenarios. Experimentation plan starts with virtual landscapes investigations, with batches of 100 to 1000 runs to ensure the stability of the model parameters one by one and combined, and to design initial configuration of landscape allowing different type of environmental performances. First, variation of the land use % are tested (Table 5) where LU types are randomly setup between 5 to 70 %, 1000 times. During those tests, human agents' behaviour types are 25% each. Initial spatial configurations will be designed (LU type % thresholds to provide high, medium, low landscape performances). Second, the land use configurations designed will be tested against a variation of human agent behaviour % (Table 5).

Table 5 - Model sensitivity analysis plan

Land use		
Type to vary	**Min-max %**	**Increment (%)**
Crops annual	5-70%	5-10-15-20-25-30-35-40-45-50-55-60-65-70
Crops perennial	5-70%	5-10-15-20-25-30-35-40-45-50-55-60-65-70
Extensive grassland	5-70%	5-10-15-20-25-30-35-40-45-50-55-60-65-70
Intensive grassland	5-70%	5-10-15-20-25-30-35-40-45-50-55-60-65-70
Scrub	5-70%	5-10-15-20-25-30-35-40-45-50-55-60-65-70
Native forest	5-70%	5-10-15-20-25-30-35-40-45-50-55-60-65-70
Exotic forest	5-70%	5-10-15-20-25-30-35-40-45-50-55-60-65-70
Human agent		
Behaviour type	**Min-max%**	**Increment (%)**
BAU %	0-100	0, 15, 25, 55, 100
EcoP %	0-100	0, 15, 25, 55, 100
CCP %	0-100	0, 15, 25, 55, 100
CCA %	0-100	0, 15, 25, 55, 100

Table 6 – Summary of the scenarios

Scenario	**Decision level**			
	Neighbours/ Peers	Local/Council	Industry	National/ Government
1	-	-	-	-
2	X	-	-	-
3	-	X	-	-
4	-	-	X	-
5	-	-	-	X

6	X	X	X	X

After sensitivity analysis, we will run scenarios for evaluating the respective and combined influence of networks on landscape performances (Table 6). Land use configurations designed on previous step and 25% of each human agent behaviour will be setup and the 6 scenarios tested (table 6). Different percentages of human agent behaviour will then be tested with one or all decision levels activated. This analysis should allow defining thresholds of land use and human behaviour and decision levels combination for positive/negative land use change/adaptation. The same experimentations and scenario testing can be run using "realistic" landscapes using GIS databases as an input. Land use is setup by the GIS database, human agent behaviours can vary (according to Table 6 increments), and the same scenarios can be tested.

These first two steps (sensitivity analysis and scenario testing) represent the fundamental analysis to define boundaries (of land use mosaics, behaviour combinations, decision level implications) for positive or negative changes and landscape adaptation. This will help define adaptation pathways at the landscape scale. The last step to consider is the activation of the six sub models one by one or combined to investigate the effects of disruption on landscape performances and agent adaptations.

6. Work development for next FY

Step 1: next FY

- NetLogo prototype development
- Land use 9 classes (artificial, water bodies, crop annual, crop perennial, grass intensive, grass extensive, scrub, native forest, exotic forest)
- Grid cells/virtual landscapes
- Human agents + entity agents
- Most of the landscape indicators
- Some sub-models for disruption (trade/ban agreements, socio-economic, diet, disease, tech)
- Sensitivity analysis
- Scenarios testing (table 6)
- Memo for scientific publication

Step 2: climate analysis for CC sub-model and biophysical agent development (not next FY)

Sensitivity again + scenario testing

Step 3: implement model with GIS option and optimisation module (not next FY)

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