**Methods**

*GMSE*

GMSE is designed to simulate dynamic decision-making by stakeholders in a social-ecological system. The stakeholders are a) the “manager” who represents an appropriate authority, for example a protected area manager or a natural resource manager, and b) the “users” who represent independent actors such as farmers. Additionally, there is a natural “resource” population, for example animals or trees, that requires management. In each simulation, the manager is attempting to get the resource population as close to a pre-determined value as possible, and the users are trying to maximise their utility on the landscape. Simulations in GMSE are comprised of four submodels that govern the social-ecological system, each of which can be individually parameterised (Fig. Sx – fig 1 Duthie et al 2018). The submodels are (1) the natural resource model which is used to simulate the biological population within the system. The natural resource model can simulate complex spatially explicit biological populations that have individual traits such as age, and population-level traits such as carrying capacity and related density-dependent mortality. Because individuals within the population have discrete traits there is inherent stochasticity within the population. (2) The observation model represents the observation process, and the associated error, whereby the manager estimates the size of the natural resource population. The manager sets policy based on the estimates rather than the actual population size, thus introducing uncertainty that exists in the real world. The submodel has four methods available which mimic commonly used biological monitoring techniques. (3) the manager model which uses the genetic algorithm (GA, see below) to develop management policies that attempt to reduce deviation of the natural resource population from the target population size. The manager achieves this by dynamically altering the cost of actions for the users thereby increasing or decreasing the ability of the users to act on the resources. (4) The user model, in which after the manager has set the policy, each user calls the GA to develop a strategy for that time step that maximises their utility (e.g. maximises their yield) given the constraints imposed by the manager. Users can choose to act on the natural resources (e.g. cull or scare) which can affect the resource population (e.g. if they choose to cull) or the landscape cell (e.g. if they choose to scare, forcing resources onto another cell). These changes then feed into the natural resource submodel in the next time step. For detailed explanations of the submodels, see Duthie et al (2018) and the documentation for the GMSE R package.

The primary approach to altering system dynamics is via the manager and user budgets. These parameters are relative rather than absolute and therefore the actual values are less important than the relationship between them. Generally, when the manager has a high relative budget, they have a greater ability to set policies that will influence the resource population in the desired way. For example, if the resource population is below the target, a manager with a relatively high budget can increase the costs of culling for the users, thus reducing the users’ ability to cull, and in turn allowing the resource population to recover. Conversely, if users have a relatively high budget, then they are more likely to be able to afford to take actions such as culling, even if the manager is setting the costs as high as possible. The budgets, and the associated dynamics, can be used to replicate various real-world systems and scenarios such as conservation conflicts, power dynamics, and lobbying (refs).

*Genetic algorithm*

The GA is the core process by which the manager develops policy and users decide upon actions. The GA mimics the process of natural selection whereby each call to the GA results in several possible strategies being initialised. Multiple iterations then allow cross-over and mutation between the initialised strategies, ensuring that budgets are not exceeded. Each subsequent iteration of strategies is selected via a fitness function and a tournament. This process results in adaptive, but not necessarily optimal, strategies for the manager and the users. In each simulation time step the GA is called by the manager and each of the users to simulate decision-making. The GA first takes the manager’s budget constraints, user action histories, and the predicted consequences of each action on the resource population and develops a strategy for the manager to reduce deviation from the target resource population size. Once the manager’s policy is established users will individually call the GA to decide upon actions that maximise their utility (e.g., agricultural yield). Users can choose from several options depending on the parameters set by the researcher. These include tending their crops or acting on the natural resources (e.g., cull, scare), all of which will have some effect on their yield. Their ability to act on the natural resource is governed by both the user budget, and the manager’s policy, in each time step.

*Parameterisation*

Landscape

In this study we have used the GMSE modelling framework to explore the effects of different investment strategies employed by a conservation manager on forest resources, in the context of an increasing human population. We simulated a forested landscape of 150 × 150 cells, where we assumed one cell was equivalent to 1 hectare, resulting in a landscape of 22,500 ha (or 225 km2). We allocated 20 “users” to the landscape, which in this case represented 20 villages or communities, each which had an equal area of spatially explicit land upon which they could act. This resulted in each village having 1,125 ha (11.24 km2) of land. We assumed the users represented agricultural communities whose primary livelihood is farming. We simulated scenarios over 50 time steps, which we assumed represented 50 years.

Resource population

The flexibility of GMSE allows for the biological resource to represent a population of a wide range of taxa. In this study we assumed the resources were trees, that the manager’s goal was to protect as many trees as possible from being felled (i.e., maintain the resource population at the starting value), and that the users were able to increase their agricultural yield by felling trees on their land. We assumed the landscape had a tree stem density of 50 ha-1, which is low for tropical forests, but plausible for a dry deciduous tropical forest (Sagar & Singh 2006), or temperate woodlands (Lunt et al 2006), resulting in a starting tree abundance of 1,125,000. Trees were randomly distributed across the landscape, reflecting natural variation. We kept tree stem density low to reduce computational load and thus simulation run time. The population dynamics of trees is difficult to capture over a 50-year time period due to slow growth and recruitment relative to animals. Furthermore, we wanted to eliminate any “noise” around the deforestation signal so that the only driver of forest loss was the effect of user actions on the trees. Therefore, despite high flexibility within GMSE for simulating realistic population dynamics, we removed the effects of natural recruitment or natural deaths (density-dependent and density-independent), resulting in a static population, excluding the effects of the users. When trees were present on a landscape cell, they reduced the agricultural yield that could be harvested by the user. Each tree on a cell reduced the cell’s yield by 8%, with the cumulative reduction in yield governed by the exponential function:

Where *y* is the yield of the cell when trees are present, *Yr* is the % reduction in yield for a single tree, and *Rt* is the number of trees remaining on the cell. Therefore, if there are 50 trees on a given cell, the cell’s yield is 1.5% of the total possible yield. If there are 25 trees remaining on a given cell then the cell’s yield increases to 12.4%, and so on.

Users

Define the landscape, and the scenarios – what are the resources, what are the objectives of the user and manager etc.