GMSE: an R package for generalised management strategy evaluation

Supporting Information 3

A. Bradley Duthie[1,3], Jeremy J. Cusack[1], Isabel L. Jones[1], Erlend B. Nilsen[2], Rocío A. Pozo[1], O. Sarobidy Rakotonarivo[1], Bram Van Moorter[2], and Nils Bunnefeld[1]

[1] Biological and Environmental Sciences, University of Stirling, Stirling, UK [2] Norwegian Institute for Nature Research, Trondheim, Norway [3] alexander.duthie@stir.ac.uk

An example of management conflict using GMSE

Agents in GMSE (managers and users) are goal-oriented, and their behaviour is therefore driven to maximise a particular utility of interest such as a target density of resources (managers), or a suitable resource or landscape harvest size (users). This model feature allows GMSE to evaluate the actions of agents in the context of their individual objectives, and to therefore quantify the degree to which those objectives are or are not achieved. When the actions of one party clashes with the objectives of another party, the objectives of one might be expressed at the expense of the other, causing conservation conflict (Redpath et al., 2013). Currently, there is no standard way to measure conservation conflict in a social-ecological system, and previous modelling approaches have not meaningfully separated agent objectives from agent actions. We suggest that a starting point to developing a useful metric of conservation conflict is to quantify the deviation of an individual's actions from their objectives (i.e., of actual actions from desired actions), the former of which is restricted by the actions of other individuals. Here we show how GMSE can be used to evaluate the amount of conflict in a simulated social-ecological system under different management options.

To demonstrate how GMSE can be used to understand conflict in social-ecological systems, we build upon the example of resource management in the main text. We consider a protected population of waterfowl that exploits agricultural land and is therefore a source of conservation conflict (e.g., Fox and Madsen, 2017; Mason et al., 2017; Tulloch et al., 2017; Cusack et al., 2018). As in the main text example, the objective of the manager is to keep waterfowl at a target abundance, while the objective of farmers is to maximise agricultural production on their landscape. Here we consider a more complex simulation, with a level of detail that more accurately reflects a scenario that might occur in a real social-ecological system. Our objective is not to model the dynamics of a specific system, but to show how GMSE could be parameterised using demographic estimates from empirical studies. We therefore consider an example population in which such estimates are well-reported and readily available.

We parameterise our model using demographic information from the Taiga Bean Goose (*Anser fabalis fabalis*), a managed population that is hunted for recreation in Fennoscandinavia (Johnson et al., 2018). Taiga Bean Geese can cause agricultural damage (Johnson et al., 2018), which could potentially lead to conflict between farmers and management objectives.

Using demographic parameters in simulations

Our goal is not to provide a detailed case study of the Taiga Bean Geese, but rather to demonstrate how such a case study would be possible in GMSE. For simplicity, here we assess conflict using only the `gmse` function to show how parameter values can be set to provide useful results. Novice R users may prefer to run all of the simulations below using the browser-based GMSE GUI by calling `gmse_gui()` from the R command line. Alternatively, experienced R users may prefer to simulate by looping time steps through `gmse_apply`, which allows more flexibility for incorporating custom sub-models and dynamically adjusting parameter values. Where available, we use estimated demographic parameter values from Johnson et al. (2018) and AEWA

(2016). Where GMSE parameter values are not available, we use reasonable values or GMSE defaults. To make model inferences for real case studies, we strongly recommend simulating across a range of parameter values when empirical estimates are unavailable, as social-ecological dynamics might be sensitive to these unknown values.

Johnson et al. (2018) recently estimated key demographic parameters of the Taiga Bean Geese from the Central Management Unit, which includes geese that breed in "Northern most Sweden, Northern Norway, Northern and Central Finland, and adjacent North-wester parts of Russia, wintering mostly in Southern Sweden and South-east Denmark" (AEWA, 2016). They estimated goose survival under ideal conditions to be ca 0.878; this can be interpreted in our model by setting mortality to `remove_pr = 1 - 0.878`. Similarly, Johnson et al. (2018) estimated mean reproductive rate and carrying capacity to be 0.55 and 93870, respectively, so we set `lambda = 0.275` (for simplicity, we simply use half the mean reproductive rate; GMSE does not currently distinguish female and male individuals) and `res_death_K = 93870`. The global abundance of Taiga Bean Geese in 2009 was ca 63000 (Fox et al., 2010), and ca 35000 in the Central Management Unit (AEWA, 2016), which we can take as a starting abundance for our simulations (`RESOURCE_ini = 35000`). And the International Single Species Action Plan has a target population size of ca 70000 in the Central Management Unit (AEWA, 2016), which we can use as a management target (`manage_target = 70000`). We simulate social-ecological dynamics over 30 time steps, which could be interpreted as years.

The code below calls `gmse` using the empirically derived parameters for Taiga Bean Geese described above. We also set `manager_budget = 10000` and `user_budget = 10000`. Further, we consider the case of a region in which farmland makes up 60% of all land, with 40% of land being 'public' (`public_land = 0.4`; which might be interpreted as any land in which stakeholders are not, or cannot be, invested in goose presence), and divide the farmland amongst 80 individual farmers (`stakeholders = 80`; `land_ownership = TRUE`). Landscape size is set to default 100 by 100 cells, so each farmer effectively owns 75 cells, which might be interpreted as hectares of land (for instructions on how to more precisely control landscape ownership, see the advanced GMSE options using `gmse_apply`). Because we need both density-dependent (`res_death_K = 93870`) and density-independent (`remove_pr = 0.122`) sources of mortality, we set `res_death_type = 3`. We assume that a single goose decreases agricultural production on a cell by 2% per time step (`res_consume = 0.02`). We further assume that the population is very well-monitored, with observers counting goose numbers on each cell of the landscape in every timestep (`observe_type = 3`) with the ability to observe one landscape cell in every direction (`agent_view = 1`). All other parameter values are set to GMSE defaults.

Simulating goose management

Below, we first only allow culling as a policy option and plot the dynamics of the social-ecological system from a single simulation. Next, we run the same simulation but also allow scaring as a policy option; we then use the model to make inferences regarding how scaring as a management option might affect goose population dynamics, agricultural production, and conservation conflict in the system. We emphasise that the simulations below are intended only to demonstrate one use of GMSE on a species of conservation interest, not to make recommendations for management of Taiga Bean Geese.

```
sim_1 <- gmse(manager_budget = 10000, user_budget = 10000, res_death_K = 93870,
              manage_target = 70000, RESOURCE_ini = 35000, plotting = FALSE,
              stakeholders = 80, land_ownership = TRUE, public_land = 0.4,
              scaring = FALSE, lambda = 0.275, remove_pr = 0.122, time_max = 30,
              res_death_type = 3, res_consume = 0.02, res_birth_K = 200000,
              observe_type = 3, agent_view = 1, converge_crit = 0.01,
              ga_mingen = 200);
```

The results of the above simulation are plotted in Figure 1 below.

```
plot_gmse_results(res = sim_1$resource, obs = sim_1$observation,
                  land = sim_1$land, agents = sim_1$agents, paras = sim_1$paras,
                  ACTION = sim_1$action, COST = sim_1$cost);
```

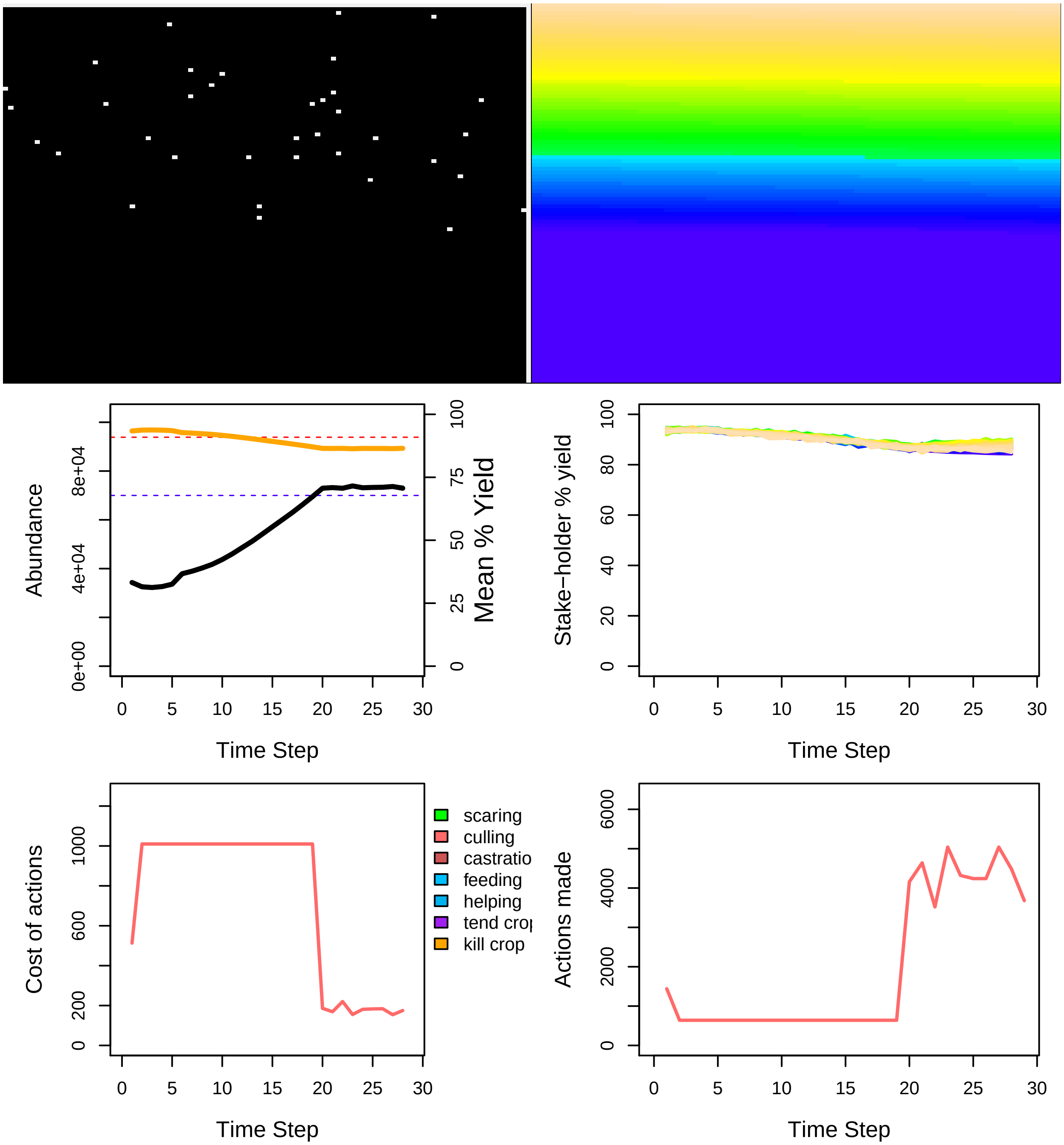

Figure 1: Results of a GMSE simulation using parameters estimated for Taiga Been Geese Central Management Unit. This example includes 80 farmers whose objective is to maximise their agricultural output, and one manager whose objective is to keep geese at a target abundance, over 30 simulated time steps. Goose locations at the end of the simulation are shown in the upper left panel, while the upper right panel shows the same landscape broken down among the 80 farmers (upper 60% of the landscape in multiple colours), along with non-agricultural land (lower 40% of the landscape in blue). Actual goose abundance is shown in the middle left panel (black solid line), along with its estimate by the manager (blue solid line). The horizontal red and blue dotted lines show goose carrying capacity and the manager's target for goose abundance, respectively. The organge line shows the total percent of landscape cell (including non-farmed cells) yield, as decreased by geese. The middle right panel shows this yield for each farmer, and for the public land (lower line in blue). The lower left panel shows the cost of culling for farmers, as set by the manager, and the lower right panel shows the total number of culls attempted by farmers over time.

Figure 1 shows the dynamics of goose abundance and agricultural yield, along with how managers react to change in abundance and farmers react to manager policy. In the case of the simulation above, managers quickly set a policy of high cost for culling, which leads to a rise in the goose population and a decrease in crop yield for farmers. After roughly 20 time steps, the goose population rises above the manager target, at which point the manager becomes more permissive of culling and the cost of culling for users therefore declines. In response, users begin to cull geese on their land, and the goose population begins to stabilise around the target of 7000 total geese. We can investigate the conflict between management policy and farmers more directly using the `plot_gmse_effort` function.

```
plot_gmse_effort(sim_1$agents, sim_1$paras, ACTION = sim_1$action,
                 COST = sim_1$cost);
```

Black lines indicate how permissive a manager is toward a particular action on a scale of 0 to 100, while coloured lines indicate how much effort farmers expend on a given action. When black lines are far below coloured lines, we can (cautiously) interpret this as a conflict between management of the goose population and farmer's interest in agricultural production. These time periods represent instances in which the manager is not permissive of a particular action (in this case culling), but farmers continue to expend effort to do the action anyway. In the case of the above simulation of potential conflict between farmers and goose conservation, conflict is highest before time step 20, where the manager is not permissive of culling because the population is below the manager's target. Once the goose population has increased above the manager's target, conflict decreases because the desired culling is permitted by managers to keep the population at a target abundance. It is worth noting that, despite conflict as we define it decreasing, agricultural damage is still relatively high after the target goose population size is achieved (Figure 1). Hence, on a broader scale, conflict might persist around the appropriate target population size rather than what actions are permitted for farmers; currently, this potential aspect of conflict is not modelled, but future versions of GMSE may attempt to incorporate such additional complexity in conflict scenarios.

We can model the consequences for goose population dynamics, agricultural production, and conservation conflict when scaring is a policy option available to the manager. The code below runs a simulation identical to the one just discussed, but with a scaring option included using the argument `scaring = TRUE`.

```
sim_2 <- gmse(manager_budget = 10000, user_budget = 10000, res_death_K = 93870,
             manage_target = 70000, RESOURCE_ini = 35000, plotting = FALSE,
             stakeholders = 80, land_ownership = TRUE, public_land = 0.4,
             scaring = TRUE, lambda = 0.275, remove_pr = 0.122, time_max = 30,
             res_death_type = 3, res_consume = 0.02, res_birth_K = 200000,
             observe_type = 3, agent_view = 1, converge_crit = 0.01,
             ga_mingen = 200);
```

The results are plotted in Figure 3.

```
plot_gmse_results(res = sim_2$resource, obs = sim_2$observation,
                  land = sim_2$land, agents = sim_2$agents, paras = sim_2$paras,
                  ACTION = sim_2$action, COST = sim_2$cost);
```

When scaring is introduced to an otherwise identical simulation (compare Figure 3 to Figure 1), the goose population increases as before, but it achieves the manager's target population size and stabilises 2-3 time steps earlier. The reason for this earlier stabilisation is due to the change in farmer's actions as a consequence of the introduced scaring policy. At the start of the simulation, managers adjust policy by quickly increasing the cost of culling and decreasing the cost of scaring. In response, farmers turn to scaring rather than culling to remove geese from their land cells (Figure 3). This is in contrast to the simulation in which scaring was not an option, and farmers simply culled as much as possible despite the high costs (Figure 1). After the population has risen to slightly above the manager's target, the cost of culling again decreases, with the manager balancing the incentivisation of culling and scaring. The consequence of scaring as an available policy also reveals some potentially unexpected outcomes, such as increased variance in among-farmer agricultural production, which arises as geese are scared from one area of the landscape to another.

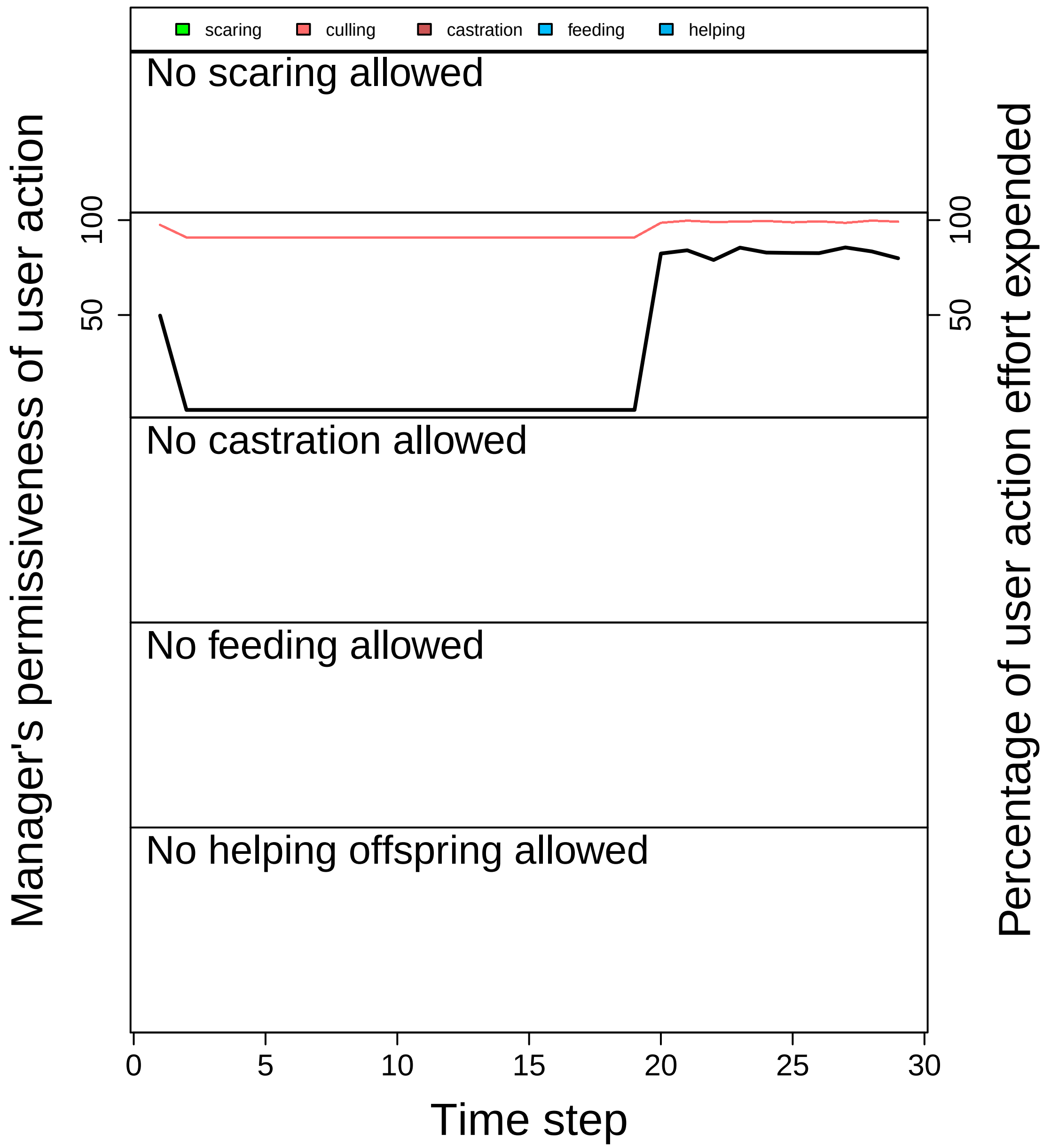

Figure 2: Permissiveness that each manager exhibits for each farmer action (black lines) and the effort that each individual farmer puts into each action over time (coloured lines). Each panel row reports a different action (in decreasing order: scaring, culling, castration, feeding, and helping). The left axis shows the permissiveness that a manager has for the focal action (black line), which is calculated as 100 minus the percent of the manager's budget that is put into increasing the cost of the focal action. For example, if the manager puts all of their effort (total budget) into increasing the cost of culling, then permissiveness of culling is 0; if the manager puts no effort into increasing culling cost, then permissiveness of culling is 100. The right axis shows effort that farmers put into an action (coloured lines), which defined as the percentage of a farmer's budget put into a particular action (note, values might not add up to 100 because farmers are not forced to use their entire budget).

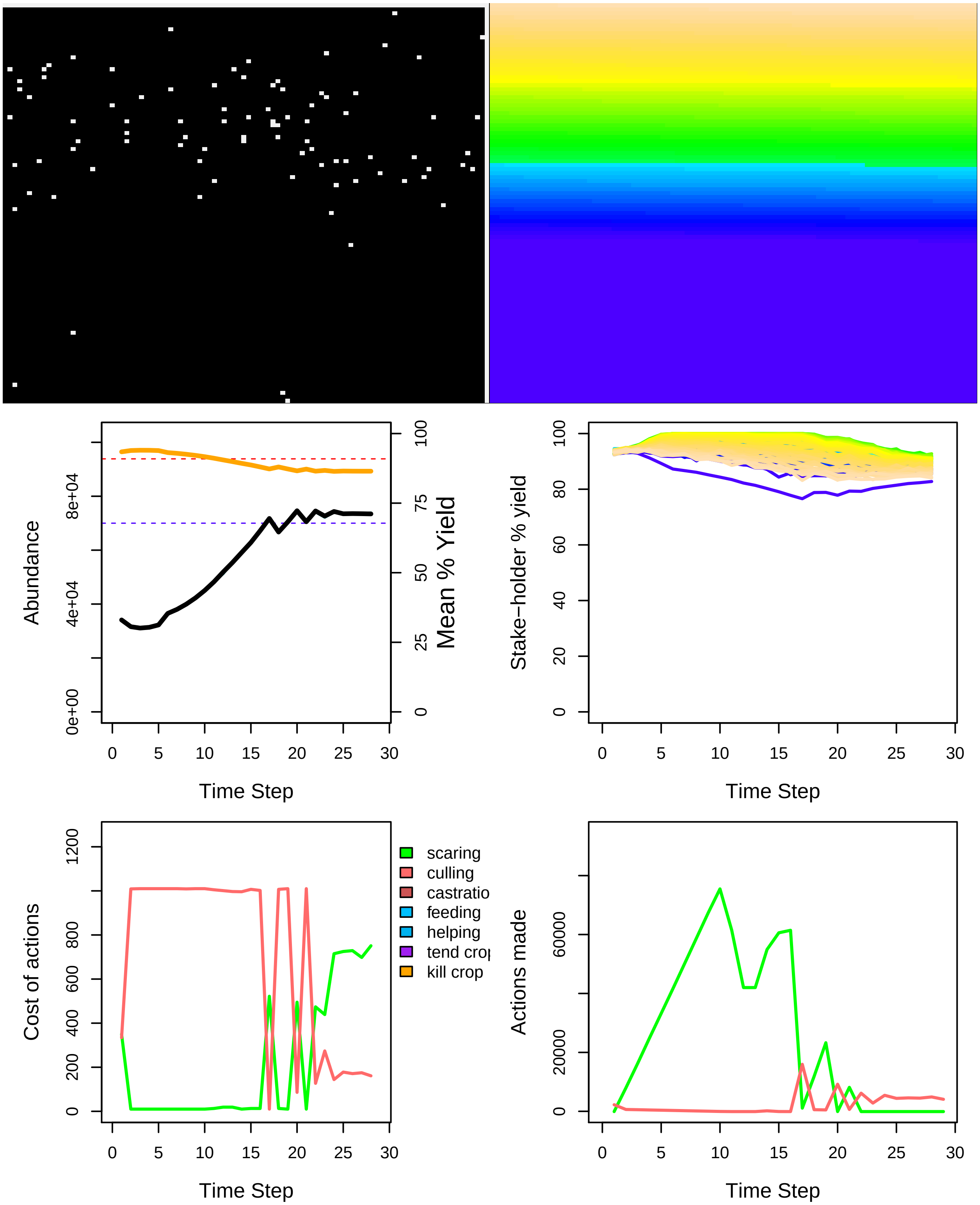

Figure 3: Results of a GMSE simulation using parameters estimated for Taiga Been Geese Central Management Unit in which scaring is permitted. Simulation output is interpreted as in Figure 1

We can use the `plot_gmse_effort` function as before to investigate how the inclusion of scaring as a policy option might affect conservation conflict. Conflict results when scaring is included are plotted in Figure 4.

```
plot_gmse_effort(sim_2$agents, sim_2$paras, ACTION = sim_2$action,
                 COST = sim_2$cost);
```

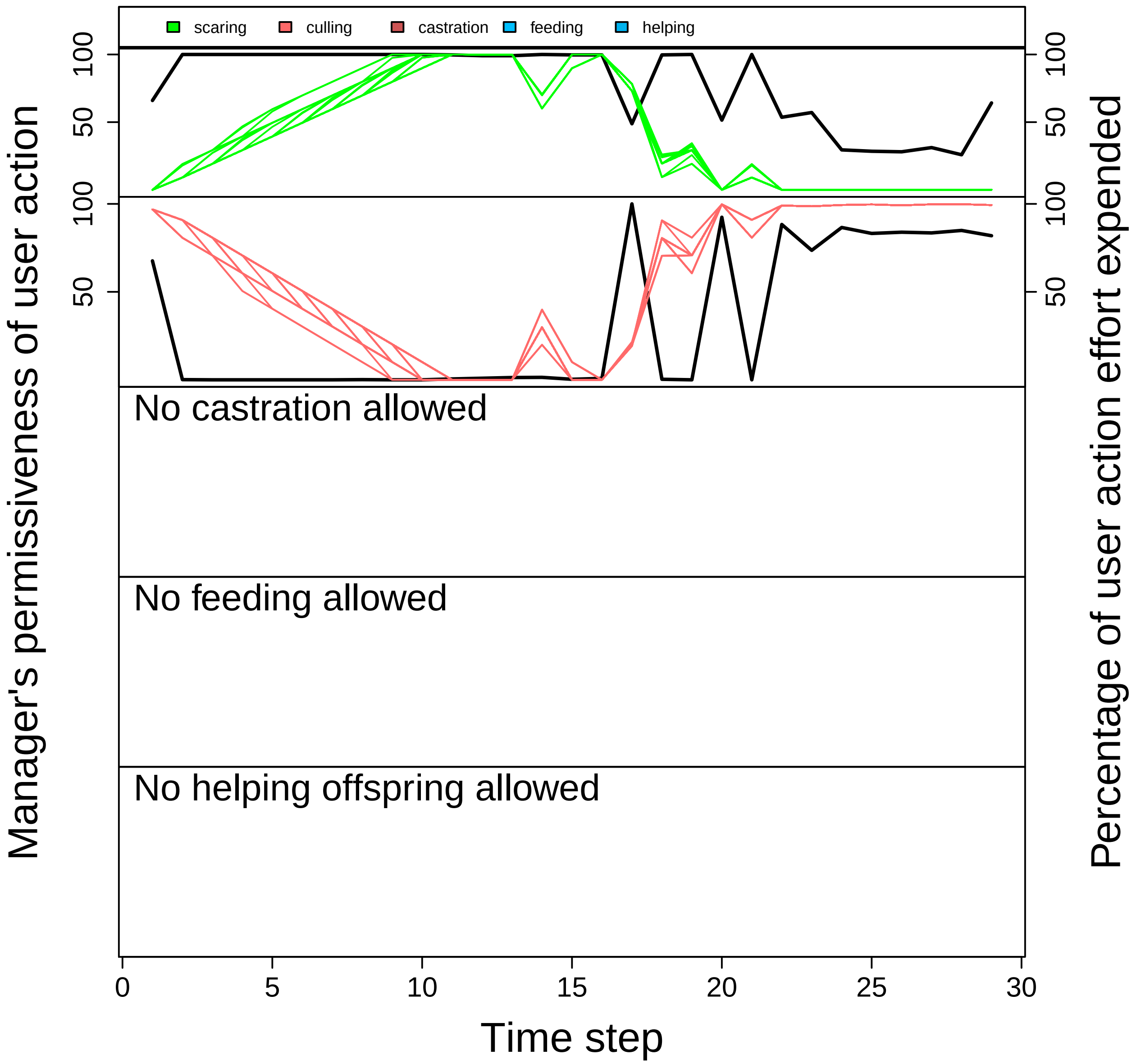

Figure 4: Permissiveness that each manager exhibits for each farmer action (black lines) and the effort that each individual farmer puts into each action over time (coloured lines) given scaring as a possible policy option. Simulation output is intepreted as in Figure 2.

Unlike the case in which culling was the only policy option (compare Figure 4 to Figure 2), the effort that farmers expended on a given action did not rise as highly above the manager's permissiveness of the action. Hence, under the conditions of this model, the inclusion of scaring as a policy option has reduced conservation conflict in the social-ecological system. We again emphasise that the simulations presented here only serve as an example for how GMSE could be used as a tool for simulating social-ecological systems and understanding the potential for conflict; it is not intended to inform policy in Taiga Bean Geese or any other specific system.

Conclusions and future development

The GMSE function `gmse` and its graphical user interface counterpart `gmse_gui` offer wide a suite of options for parameterising simulations to fit empirical case studies of conservation interest using default GMSE natural resource, observation, manager, and user sub-models. Future development of these sub-models might usefully incorporate additional details relevant to specific case studies, such population structure, multiple natural resource and user types, or different manager policy and user action possibilities. Requests for new features and contributions to GMSE can be made through GitHub. Additionally, where entirely different types of sub-models are required, the `gmse_apply` function can be used to more flexibly simulate social-ecological systems.

References

AEWA (2016). International single species action plan for the conservation of the Taiga Bean Goose (Anser fabalis fabalis).

Cusack, J. J., Duthie, A. B., Rakotonarivo, S., Pozo, R. A., Mason, T. H. E., Månsson, J., Nilsson, L., Tombre, I. M., Eythórsson, E., Madsen, J., Tulloch, A., Hearn, R. D., Redpath, S., and Bunnefeld, N. (2018). Time series analysis reveals synchrony and asynchrony between conflict management effort and increasing large grazing bird populations in northern Europe. *Conservation Letters*, page e12450.

Fox, A. D., Ebbinge, B. S., Mitchell, C., Heinicke, T., Aarvak, T., Colhoun, K., Clausen, P., Dereliev, S., Faragö, S., Koffijberg, K., Kruckenberg, H., Loonen, M. J., Madsen, J., Mooij, J., Musil, P., Nilsson, L., Pihl, S., and Van Der Jeugd, H. (2010). Current estimates of goose population sizes in western Europe, a gap analysis and an assessment of trends. *Ornis Svecica*, 20(3-4):115–127.

Fox, A. D. and Madsen, J. (2017). Threatened species to super-abundance: The unexpected international implications of successful goose conservation. *Ambio*, 46(s2):179–187.

Johnson, F. A., Alhainen, M., Fox, A. D., Madsen, J., and Guillemain, M. (2018). Making do with less: Must sparse data preclude informed harvest strategies for European waterbirds. *Ecological Applications*, 28(2):427–441.

Mason, T. H., Keane, A., Redpath, S. M., and Bunnefeld, N. (2017). The changing environment of conservation conflict: geese and farming in Scotland. *Journal of Applied Ecology*, pages 1–12.

Redpath, S. M., Young, J., Evely, A., Adams, W. M., Sutherland, W. J., Whitehouse, A., Amar, A., Lambert, R. A., Linnell, J. D. C., Watt, A., and Gutiérrez, R. J. (2013). Understanding and managing conservation conflicts. *Trends in Ecology & Evolution*, 28(2):100–109.

Tulloch, A. I. T., Nicol, S., and Bunnefeld, N. (2017). Quantifying the expected value of uncertain management choices for over-abundant Greylag Geese. *Biological Conservation*, 214:147–155.