Advanced case study options

GMSE: an R package for generalised management strategy evaluation (Supporting Information 4)

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Fine-tuning simulation conditions using `gmse_apply`

Here we demonstrate how simulations in GMSE can be more fine-tuned to specific empirical situations through the use of `gmse_apply`. To do this, we use the same scenario described in SI3; we first recreate the basic scenario run in `gmse` using `gmse_apply`, and then build in additional modelling details including (1) custom placement of user land, (2) parameterisation of individual user budgets, and (3) density-dependent movement of resources. We emphasise that these simulations are provided only to demonstrate the use of GMSE, and specifically to show the flexibility of the `gmse_apply` function, not to accurately recreate the dynamics of a specific system or make management recommendations.

We reconsider the case of a protected waterfowl population that exploits agricultural land (e.g., Fox and Madsen, 2017; Mason et al., 2017; Tulloch et al., 2017; Cusack et al., 2018). The manager attempts to keep the watefowl at a target abundance, while users (farmers) attempt to maximise agricultural yield on the land that they own. We again parameterise our model using demographic information from the Taiga Bean Goose (*Anser fabalis fabalis*), as reported by Johnson et al. (2018) and AEWA (2016). Relevant parameter values are listed in the table below.

Table 1: GMSE simulation parameter values inspired by Johnson et al. (2018) and AEWA (2016)

Parameter	Value	Description
`remove_pr`	0.122	Goose density-independent mortality probability
`lambda`	0.275	Expected offspring production per time step
`res_death_K`	93870	Goose carrying capacity (on adult mortality)
`RESOURCE_ini`	35000	Initial goose abundance
`manage_target`	70000	Manager's target goose abundance
`res_death_type`	3	Mortality (density and density-independent sources)

Additionally, we continue to use the following values for consistency, except in the case of `stakeholders`, where we reduce the number of farmers to `stakeholders = 8`. This is done to for two reasons. First, it speeds up simulations for the purpose of demonstration; second, it makes the presentation of our custom landscape ownership easier to visualise (see below).

Table 2: Non-default GMSE parameter values chosen by authors

Parameter	Value	Description
`manager_budget`	10000	Manager's budget for setting policy options
`user_budget`	10000	Users' budgets for actions
`public_land`	0.4	Proportion of the landscape that is public

Parameter	Value	Description
`stakeholders`	8	Number of stakeholders
`land_ownership`	TRUE	Users own landscape cells
`res_consume`	0.02	Landscape cell output consumed by a resource
`observe_type`	3	Observation model type (survey)
`agent_view`	1	Cells managers can see when conducting a survey

All other values are set to GMSE defaults, except where specifically noted otherwise.

Re-creating `gmse` simulations using `gmse_apply`

We now recreate the simulations in SI3, which were run using the `gmse` function, in `gmse_apply`. Doing so requires us to first initialise simulations using one call of `gmse_apply`, then loop through multiple time steps that again call `gmse_apply`; results of interest are recorded in a data frame (`sim_sum_1`). Following the protocol introduced in SI2, we can call the initialising simulation `sim_old`, and use the code below to read in the relevant parameter values.

```
sim_old  <- gmse_apply(get_res = "Full", remove_pr = 0.122, lambda = 0.275,
                       res_death_K = 93870, RESOURCE_ini = 35000,
                       manage_target = 70000, res_death_type = 3,
                       manager_budget = 10000, user_budget = 100000,
                       public_land = 0.4, stakeholders = 8, res_consume = 0.02,
                       res_birth_K = 200000, land_ownership = TRUE,
                       observe_type = 3, agent_view = 1, converge_crit = 0.01,
                       ga_mingen = 200);
```

Note that the argument `get_res = "Full"` causes `sim_old` to retain all of the relevant data structures for simulating a new time step and recording simulation results. This includes the key simulation output, which is located in `sim_old$basic_output`, which is printed below.

```
## $resource_results
## [1] 34212
##
## $observation_results
## [1] 34212
##
## $manager_results
##           resource_type scaring culling castration feeding help_offspring
## policy_1              1      NA     515         NA      NA             NA
##
## $user_results
##          resource_type scaring culling castration feeding help_offspring
## Manager              1      NA       0         NA      NA             NA
## user_1               1      NA     194         NA      NA             NA
## user_2               1      NA     194         NA      NA             NA
## user_3               1      NA     194         NA      NA             NA
## user_4               1      NA     194         NA      NA             NA
## user_5               1      NA     194         NA      NA             NA
## user_6               1      NA     194         NA      NA             NA
## user_7               1      NA     194         NA      NA             NA
## user_8               1      NA     194         NA      NA             NA
##          tend_crops kill_crops
```

```
## Manager         NA         NA
## user_1          NA         NA
## user_2          NA         NA
## user_3          NA         NA
## user_4          NA         NA
## user_5          NA         NA
## user_6          NA         NA
## user_7          NA         NA
## user_8          NA         NA
```

We can then loop over 30 time steps to recreate the simulations from SI3. In these simulations, we are specifically interested in the resource and observation outputs, as well as the manager policy and user actions for culling, which we record below in the data frame `sim_sum_1`. The inclusion of the argument `old_list` tells `gmse_apply` to use parameters and values from the list `sim_old` in the new time step.

```
sim_sum_1 <- matrix(data = NA, nrow = 30, ncol = 5);
for(time_step in 1:30){
    sim_new                 <- gmse_apply(get_res = "Full", old_list = sim_old);
    sim_sum_1[time_step, 1] <- time_step;
    sim_sum_1[time_step, 2] <- sim_new$basic_output$resource_results[1];
    sim_sum_1[time_step, 3] <- sim_new$basic_output$observation_results[1];
    sim_sum_1[time_step, 4] <- sim_new$basic_output$manager_results[3];
    sim_sum_1[time_step, 5] <- sum(sim_new$basic_output$user_results[,3]);
    sim_old                 <- sim_new;
}
colnames(sim_sum_1) <- c("Time", "Pop_size", "Pop_est", "Cull_cost",
                         "Cull_count");
print(sim_sum_1);
```

```
##       Time Pop_size Pop_est Cull_cost Cull_count
##  [1,]    1    32588   32588      1010        792
##  [2,]    2    32337   32337      1009        792
##  [3,]    3    32716   32716      1010        792
##  [4,]    4    33426   33426      1009        792
##  [5,]    5    37736   37736      1010        790
##  [6,]    6    38925   38925      1009        792
##  [7,]    7    40174   40174      1010        792
##  [8,]    8    41861   41861      1010        791
##  [9,]    9    43872   43872      1010        792
## [10,]   10    46015   46015      1010        792
## [11,]   11    48538   48538      1010        792
## [12,]   12    50934   50934      1010        792
## [13,]   13    53477   53477      1010        792
## [14,]   14    56075   56075      1010        792
## [15,]   15    59169   59169      1010        792
## [16,]   16    62448   62448      1010        792
## [17,]   17    65731   65731      1010        792
## [18,]   18    69512   69512      1010        792
## [19,]   19    73333   73333        24      23105
## [20,]   20    53671   53671      1010        792
## [21,]   21    56452   56452      1010        792
## [22,]   22    59512   59512      1010        792
## [23,]   23    62773   62773      1010        792
## [24,]   24    66092   66092      1010        792
## [25,]   25    70103   70103       777       1024
```

```
## [26,]   26    73672   73672        22      24265
## [27,]   27    52822   52822      1010        792
## [28,]   28    55601   55601      1010        792
## [29,]   29    58550   58550      1010        792
## [30,]   30    61768   61768      1010        792
```

The above output from `sim_sum_1` shows the data frame that holds the information we were interested in pulling out of our simulation results. All of this information was available under the list element `sim_new$basic_output`, but other list elements of `sim_new` might also be useful to record. It is important to remember that this example of `gmse_apply` is using the default resource, observation, manager, and user sub-models. Custom sub-models could produce different outputs in `sim_new` (see SI2 for examples). For default sub-models, there are some list elements that might be especially useful. These elements can potentially be edited *within the above loop* to dynamically adjust simulations. For more explanation of built-in GMSE data arrays, see SI7.

- `sim_new$resource_array`: A table holding all information on resources. Rows correspond to discrete resources, and columns correspond to resource properties: (1) ID, (2-4) types (not currently in use), (5) x-location, (6) y-location, (7) movement parameter, (8) time, (9) density independent mortality parameter (`remove_pr`), (10) reproduction parameter (`lambda`), (11) offspring number, (12) age, (13-14) observation columns, (15) consumption rate (`res_consume`), and (16-20) recorded experiences of user actions (e.g., was the resource culled or scared?).
- `sim_new$AGENTS`: A table holding basic information on agents (manager and users). Rows correspond to a unique agent, and columns correspond to agent properties: (1) ID, (2) type (0 for the manager, 1 for users), (3-4) additional type options not currently in use, (5-6), x and y locations (usually ignored), (7) movement parameter (usually ignored), (8) time, (9) agent's viewing ability in cells (`agent_view`), (10) error parameter, (11-12) values for holding marks and tallies of resources, (13-15) values for holding observations, (16) yield from landscape cells, (17) budget (`manager_budget` and `user_budget`).
- `sim_new$observation_vector`: Estimate of total resource number from the observation model (`observation_array` also holds this information in a different way depending on `observe_type`)
- `sim_new$LAND`: The landscape on which interactions occur, which is stored as a 3D array with `land_dim_1` rows, `land_dim_2` columns, and 3 layers. Layer 1 (`sim_new$LAND[,,1]`) is not currently used in default sub-models, but could be used to store values that affect resources and agents. Layer 2 (`sim_new$LAND[,,2]`) stores crop yield from a cell, and layer 3 (`sim_new$LAND[,,3]`) stores the owner of the cell (value corresponds to the agent's ID).
- `sim_new$manage_vector`: The cost of each action as set by the manager. For even more fine-tuning, individual costs for the actions of each agent can be set for each user in `sim_new$manager_array`.
- `sim_new$user_vector`: The total number of actions performed by each user. A more detailed breakdown of actions by individual users is held in `sim_new$user_array`.

Next, we show how to adjust the landscape to manually set land ownership in `gmse_apply`.

1. Custom placement of user land

By default, all farmers in GMSE are allocated the same number of landscape cells, which are simply placed in order of the farmer's ID. Public land is produced by placing landscape cells that are technically owned by the manager, and therefore have landscape cell values of 1. The image below shows this landscape for the eight farmers from `sim_old`.

```
image(x = sim_old$LAND[,,3], col = topo.colors(9), xaxt = "n", yaxt = "n");
```

We can change the ownership of cells by manipulating `sim_old$LAND[,,3]`. First we initialise a new `sim_old` below.

```
sim_old  <- gmse_apply(get_res = "Full", remove_pr = 0.122, lambda = 0.275,
                       res_d4eath_K = 93870, RESOURCE_ini = 35000,
```

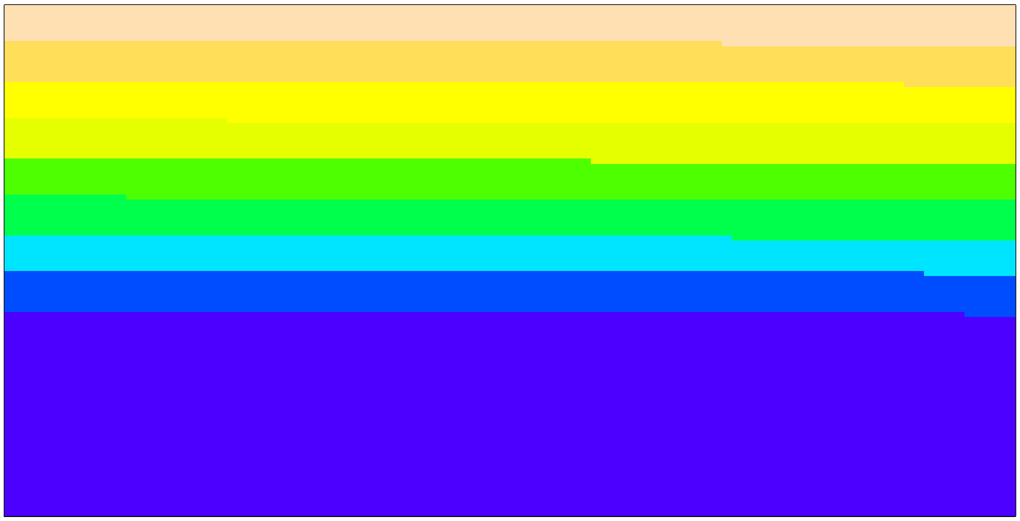

Figure 1: Default position of land ownership by farmers.

```
                         manage_target = 70000, res_death_type = 3,
                         manager_budget = 10000, user_budget = 10000,
                         public_land = 0.4, stakeholders = 8, res_consume = 0.02,
                         res_birth_K = 200000, land_ownership = TRUE,
                         observe_type = 3, agent_view = 1, converge_crit = 0.01,
                         ga_mingen = 200);
```

Because we have not specified landscape dimensions in the above, the landscape reverts to the default size of 100 by 100 cells. We can then manually assign landscape cells to the eight farmers, whose IDs range from 2-9 (ID value 1 is the manager). Below we do this to make eight different sized farms.

```
sim_old$LAND[1:20,   1:20,  3] <- 2;
sim_old$LAND[1:20,  21:40,  3] <- 3;
sim_old$LAND[1:20,  41:60,  3] <- 4;
sim_old$LAND[1:20,  61:80,  3] <- 5;
sim_old$LAND[1:20,  81:100, 3] <- 6;
sim_old$LAND[21:40,  1:50,  3] <- 7;
sim_old$LAND[21:40, 51:100, 3] <- 8;
sim_old$LAND[41:60,  1:100, 3] <- 9;
sim_old$LAND[61:100, 1:100, 3] <- 1; # Public land
image(x = sim_old$LAND[,,3], col = topo.colors(9), xaxt = "n", yaxt = "n");
```

The above image shows the modified landscape stored in `sim_old`, which can now be incorporated into simulations using `gmse_apply`. We can think of all the plots on the left side of the landscape as farms of various sizes, while the blue area of the landscape on the right is public land.

2. Parameterisation of individual user budgets

Perhaps we want to assume that farmers have different budgets, which are correlated in some way to the number of landscape cells that they own. Custom user budgets can be set by manipulating `sim_old$AGENTS`, the last column of which (column 17) holds the budget for each user. Agent IDs (as stored on the landscape above) correspond to rows of `sim_old$AGENTS`, so individual budgets can be directly input as desired. We can do this manually (e.g., `sim_old$AGENTS[2, 17] <- 4000`), or, alternatively, if farmer budget positively

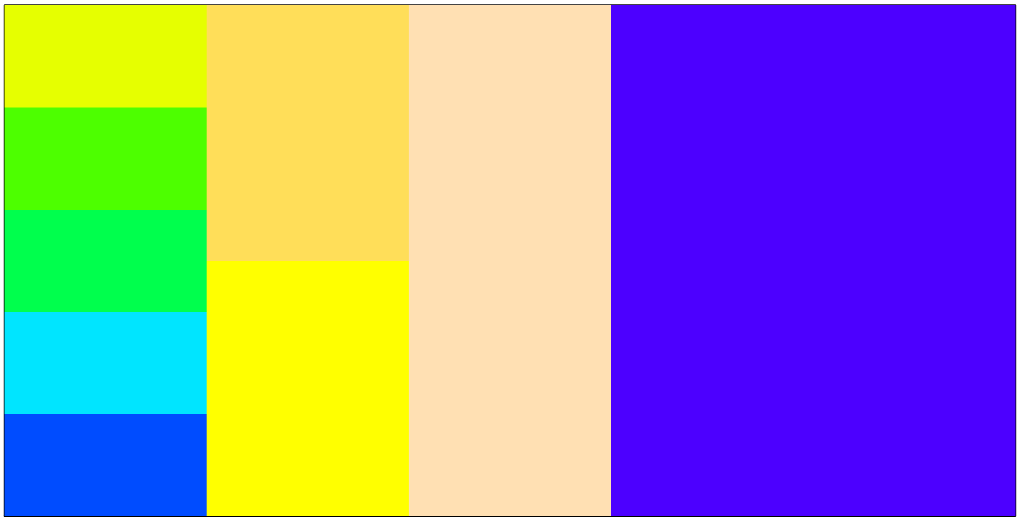

Figure 2: Land ownership by farmers as customised in gmse_apply.

correlates to landscape owned, we can use a loop to input values as below.

```
for(ID in 2:9){
    cells_owned            <- sum(sim_old$LAND[,,3] == ID);
    sim_old$AGENTS[ID, 17] <- 10 * cells_owned;
}
```

The number of cells owned by the manager (1) and each farmer (2-8) is therefore listed in the table below.

ID	1	2	3	4	5	6	7	8	9
Budget	10000	4000	4000	4000	4000	4000	10000	10000	20000

As with `sim_old$LAND` values, changes to `sim_old$AGENTS` will be retained in simulations looped through `gmse_apply`.

3. Density-dependent movement of resources

Lastly, we consider a more nuanced change to simulations, in which the rules for movement of resources are modified to account for density-dependence. Assume that geese tend to avoid aggregating, such that if a goose is located on the same cell as too many other geese, then it will move at the start of a time step. Programming this movement rule can be accomplished by creating a new function to apply to the resource data array `sim_old$resource_array`. Below, a custom function is defined that causes a goose to move up to 5 cells in any direction if it finds itself on a cell with more than 10 other geese. As with default GMSE simulations, movement is based on a torus landscape (where no landscape edge exists, so that if resources move off of one side of the landscape they appear on the opposite side). We will use this custom function to modify `sim_old$resource_array` prior to running `gmse_apply`, thereby modelling a custom-built process affecting resource distribution that is integrated into GMSE.

```r
avoid_aggregation <- function(sim_resource_array, land_dim_1 = 100,
                              land_dim_2 = 100){
    goose_number <- dim(sim_resource_array)[1]  # How many geese are there?
    for(goose in 1:goose_number){               # Loop through all rows of geese
        x_loc  <- sim_resource_array[goose, 5];
        y_loc  <- sim_resource_array[goose, 6];
        shared <- sum( sim_resource_array[,5] == x_loc &
                       sim_resource_array[,6] == y_loc);
        if(shared > 10){
            new_x <- x_loc + sample(x = -5:5, size = 1);
            new_y <- y_loc + sample(x = -5:5, size = 1);
            if(new_x < 0){ # The 'if' statements below apply the torus
                new_x <- land_dim_1 + new_x;
            }
            if(new_x >= land_dim_1){
                new_x <- new_x - land_dim_1;
            }
            if(new_y < 0){
                new_y <- land_dim_2 + new_x;
            }
            if(new_y >= land_dim_2){
                new_y <- new_y - land_dim_2;
            }
            sim_resource_array[goose, 5] <- new_x;
            sim_resource_array[goose, 6] <- new_y;
        }
    }
    return(sim_resource_array);
}
```

With the above function written, we can apply the new movement rule along with our custom farm placement and custom farmer budgets to the simulation of goose population dynamics.

Simulation with custom farms, budgets, and goose movement

Below shows an example of `gmse_apply` with custom landscapes, farmer budgets, and density-dependent goose movement rules.

```r
# First initialise a simulation
sim_old  <- gmse_apply(get_res = "Full", remove_pr = 0.122, lambda = 0.275,
                       res_death_K = 93870, RESOURCE_ini = 35000,
                       manage_target = 70000, res_death_type = 3,
                       manager_budget = 10000, user_budget = 10000,
                       public_land = 0.4, stakeholders = 8, res_consume = 0.02,
                       res_birth_K = 200000, land_ownership = TRUE,
                       observe_type = 3, agent_view = 1, converge_crit = 0.01,
                       ga_mingen = 200, res_move_type = 0);
# By setting `res_move_type = 0`, no resource movement will occur in gmse_apply
# Adjust the landscape ownership below
sim_old$LAND[1:20,   1:20,  3] <- 2;
sim_old$LAND[1:20,  21:40,  3] <- 3;
sim_old$LAND[1:20,  41:60,  3] <- 4;
sim_old$LAND[1:20,  61:80,  3] <- 5;
```

```r
sim_old$LAND[1:20,  81:100, 3] <- 6;
sim_old$LAND[21:40,  1:50,  3] <- 7;
sim_old$LAND[21:40, 51:100, 3] <- 8;
sim_old$LAND[41:60,  1:100, 3] <- 9;
sim_old$LAND[61:100, 1:100, 3] <- 1;
# Change the budgets of each farmer based on the land they own
for(ID in 2:9){
    cells_owned            <- sum(sim_old$LAND[,,3] == ID);
    sim_old$AGENTS[ID, 17] <- 10 * cells_owned;
}
# Begin simulating time steps for the system
sim_sum_2 <- matrix(data = NA, nrow = 30, ncol = 5);
for(time_step in 1:30){
    # Apply the new movement rules at the beginning of the loop
    sim_old$resource_array  <- avoid_aggregation(sim_resource_array =
                                                    sim_old$resource_array);
    # Next, move on to simulate (old_list remembers that res_move_type = 0)
    sim_new                 <- gmse_apply(get_res = "Full", old_list = sim_old);
    sim_sum_2[time_step, 1] <- time_step;
    sim_sum_2[time_step, 2] <- sim_new$basic_output$resource_results[1];
    sim_sum_2[time_step, 3] <- sim_new$basic_output$observation_results[1];
    sim_sum_2[time_step, 4] <- sim_new$basic_output$manager_results[3];
    sim_sum_2[time_step, 5] <- sum(sim_new$basic_output$user_results[,3]);
    sim_old                 <- sim_new;
}
colnames(sim_sum_2) <- c("Time", "Pop_size", "Pop_est", "Cull_cost",
                         "Cull_count");
print(sim_sum_2);
```

```
##       Time Pop_size Pop_est Cull_cost Cull_count
##  [1,]    1    33926   33926      1010         52
##  [2,]    2    34402   34402      1001         52
##  [3,]    3    35637   35637      1010         52
##  [4,]    4    37565   37565      1001         52
##  [5,]    5    43479   43479      1010         52
##  [6,]    6    45757   45757       992         60
##  [7,]    7    48457   48457      1010         52
##  [8,]    8    51326   51326      1004         52
##  [9,]    9    54497   54497      1009         52
## [10,]   10    58007   58007      1010         52
## [11,]   11    61812   61812      1008         52
## [12,]   12    65453   65453      1010         52
## [13,]   13    69460   69460      1010         52
## [14,]   14    73976   73976        10       5391
## [15,]   15    73467   73467        10       5418
## [16,]   16    72910   72910        10       5466
## [17,]   17    72197   72197        10       5416
## [18,]   18    71518   71518        10       5474
## [19,]   19    70711   70711        10       5404
## [20,]   20    70106   70106        51       1174
## [21,]   21    73508   73508        10       5438
## [22,]   22    72688   72688        10       5377
## [23,]   23    71865   71865        10       5469
## [24,]   24    70943   70943        10       5438
```

```
## [25,]   25   70857   70857          10         5442
## [26,]   26   72162   72162          10         5427
## [27,]   27   73755   73755          10         5415
## [28,]   28   75871   75871          10         5463
## [29,]   29   77993   77993          10         5398
## [30,]   30   80489   80489          10         5496
```

Conclusions

In this example, we showed how the built-in resource, observation, manager, and user sub-models can be customised by manipulating the data within the data structures that they use. The goal was to show how software users can work with these existing sub-models and data structures to customise GMSE simulations. Readers seeking even greater flexibility (e.g., replacing an entire built-in sub-model with a custom sub-model) should refer to SI2 that introduces `gmse_apply` more generally. Future versions of GMSE are likely to expand on the built-in options available for simulation; requests for such expansions, or contributions, can be submitted to GitHub.

References

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