Use of the gmse_apply function

GMSE: an R package for generalised management strategy evaluation (Supporting Information 2)

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Extended introduction to the GMSE apply function (`gmse_apply`)

The `gmse_apply` function is a flexible function that allows for user-defined sub-functions calling resource, observation, manager, and user models. Where such models are not specified, predefined GMSE sub-models 'resource', 'observation', 'manager', and 'user' are run by default. Any type of sub-model (e.g., numerical, individual-based) is permitted as long as the input and output are appropriately specified. Only one time step is simulated per call to `gmse_apply`, so the function must be looped for simulation over time. Where model parameters are needed but not specified, defaults from GMSE are used. Here we demonstrate some uses of `gmse_apply`, and how it might be used to simulate myriad management scenarios *in silico*.

A simple run of `gmse_apply()` returns one time step of GMSE using predefined sub-models and default parameter values.

```
sim_1 <- gmse_apply();
```

For `sim_1`, the default 'basic' results are returned as below, which summarise key values for all sub-models.

```
print(sim_1);
```

```
## $resource_results
## [1] 1097
##
## $observation_results
## [1] 725.6236
##
## $manager_results
##          resource_type scaring culling castration feeding help_offspring
## policy_1             1      NA      71         NA      NA             NA
##
## $user_results
##         resource_type scaring culling castration feeding help_offspring
## Manager             1      NA       0         NA      NA             NA
## user_1              1      NA      14         NA      NA             NA
## user_2              1      NA      14         NA      NA             NA
## user_3              1      NA      14         NA      NA             NA
## user_4              1      NA      14         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
```

Note that in the case above we have the total abundance of resources returned (`sim_1$resource_results`), the estimate of resource abundance from the observation function (`sim_1$observation_results`), the costs the manager sets for the only available action of culling (`sim_1$manager_results`), and the number of culls attempted by each user (`sim_1$user_results`). By default, only one resource type is used, but custom sub-functions could potentially allow for models with multiple resource types. Any custom sub-functions can replace GMSE predefined functions, provided that they have appropriately defined inputs and outputs (see GMSE documentation). For example, we can define a very simple logistic growth function to send to `res_mod` instead.

```
alt_res <- function(X, K = 2000, rate = 1){
    X_1 <- X + rate*X*(1 - X/K);
    return(X_1);
}
```

The above function takes in a population size of `X` and returns a value `X_1` based on the population intrinsic growth rate `rate` and carrying capacity `K`. Iterating the logistic growth model by itself under default parameter values with a starting population of 100 will cause the population to increase to carrying capacity in ca seven time steps The function can be substituted into `gmse_apply` to use it instead of the predefined GMSE resource model.

```
sim_2 <- gmse_apply(res_mod = alt_res, X = 100, rate = 0.3);
```

The `gmse_apply` function will find the parameters it needs to run the `alt_res` function in place of the default resource function, either by running the default function values (e.g., `K = 2000`) or values specified directly into `gmse_apply` (e.g., `X = 100` and `rate = 0.3`). If an argument to a custom function is required but not provided either as a default or specified in `gmse_apply`, then an error will be returned. Results for the above `sim_2` are returned below.

```
print(sim_2);
```

```
## $resource_results
## [1] 128
##
## $observation_results
## [1] 136.0544
##
## $manager_results
##          resource_type scaring culling castration feeding help_offspring
## policy_1             1      NA      71         NA      NA             NA
##
## $user_results
##         resource_type scaring culling castration feeding help_offspring
## Manager             1      NA       0         NA      NA             NA
## user_1              1      NA      14         NA      NA             NA
## user_2              1      NA      14         NA      NA             NA
## user_3              1      NA      14         NA      NA             NA
## user_4              1      NA      14         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
```

How gmse_apply integrates across sub-models

To integrate across different types of sub-models, `gmse_apply` translates between vectors and arrays between each sub-model. For example, because the default GMSE observation model requires a resource array with particular requirements for column identites, when a resource model sub-function returns a vector, or a list with a named element 'resource_vector', this vector is translated into an array that can be used by the observation model. Specifically, each element of the vector identifies the abundance of a resource type (and hence will usually be just a single value denoting abundance of the only focal population). If this is all the information provided, then a 'resource_array' will be made with default GMSE parameter values with an identical number of rows to the abundance value (floored if the value is a non-integer; non-default values can also be put into this transformation from vector to array if they are specified in `gmse_apply`, e.g., through an argument such as `lambda = 0.8`). Similarly, a `resource_array` is also translated into a vector after the default individual-based resource model is run, should a custom observation model require simple abundances instead of an array. The same is true of `observation_vector` and `observation_array` objects returned by observation models, of `manager_vector` and `manager_array` (i.e., `COST` in the `gmse` function) objects returned by manager models, and of `user_vector` and `user_array` (i.e., `ACTION` in the `gmse` function) objects returned by user models. At each step, a translation between the two is made, with necessary adjustments that can be tweaked through arguments to `gmse_apply` when needed. Alternative observation, manager, and user, sub-models, for example, are defined below; note that each requires a vector from the preceding model.

```
# Alternative observation sub-model
alt_obs <- function(resource_vector){
    X_obs <- resource_vector - 0.1 * resource_vector;
    return(X_obs);
}

# Alternative manager sub-model
alt_man <- function(observation_vector){
    policy <- observation_vector - 1000;
    if(policy < 0){
        policy <- 0;
    }
    return(policy);
}

# Alternative user sub-model
alt_usr <- function(manager_vector){
    harvest <- manager_vector + manager_vector * 0.1;
    return(harvest);
}
```

All of these sub-models are completely deterministic, so when run with the same parameter combinations, they produce replicable outputs.

```
gmse_apply(res_mod = alt_res, obs_mod = alt_obs,
           man_mod = alt_man, use_mod = alt_usr, X = 1000);
```

```
## $resource_results
## [1] 1500
##
## $observation_results
## [1] 1350
##
## $manager_results
## [1] 350
```

```
##
## $user_results
## [1] 385
```

Note that the `manager_results` and `user_results` are ambiguous here, and can be interpreted as desired – e.g., as total allowable catch and catches made, or as something like costs of catching set by the manager and effort to catching made by the user. Hence, while manger output is set in terms of costs of performing each action, and user output is set in terms of action attempts, this need not be the case when using `gmse_apply` (though it should be recognised when using default GMSE manager and user functions). GMSE default sub-models can be added in at any point.

```r
gmse_apply(res_mod = alt_res, obs_mod = observation,
           man_mod = alt_man, use_mod = alt_usr, X = 1000);
```

```
## $resource_results
## [1] 1500
##
## $observation_results
## [1] 1587.302
##
## $manager_results
## [1] 587.3016
##
## $user_results
## [1] 646.0317
```

It is possible to, e.g., specify a simple resource and observation model, but then take advantage of the genetic algorithm to predict policy decisions and user actions (see SI5 for a fisheries example). This can be done by using the default GMSE manager and user functions (written below explicitly, though this is not necessary).

```r
gmse_apply(res_mod = alt_res, obs_mod = alt_obs,
           man_mod = manager, use_mod = user, X = 1000);
```

```
## $resource_results
## [1] 1500
##
## $observation_results
## [1] 1350
##
## $manager_results
##          resource_type scaring culling castration feeding help_offspring
## policy_1             1      NA      60         NA      NA             NA
##
## $user_results
##         resource_type scaring culling castration feeding help_offspring
## Manager             1      NA       0         NA      NA             NA
## user_1              1      NA      16         NA      NA             NA
## user_2              1      NA      16         NA      NA             NA
## user_3              1      NA      16         NA      NA             NA
## user_4              1      NA      16         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
```

Running GMSE simulations by looping `gmse_apply`

Instead of using the `gmse` function, multiple simulations of GMSE can be run by calling `gmse_apply` through a loop, reassigning outputs where necessary for the next generation. This is best accomplished using the argument `old_list`, which allows previous full results from `gmse_apply` to be reinserted into the `gmse_apply` function. The argument `old_list` is `NULL` by default, but can instead take the output of a previous full list return of `gmse_apply`. This `old_list` produced when `get_res = Full` includes all data structures and parameter values necessary for a unique simulation of GMSE. Note that custom functions sent to `gmse_apply` still need to be specified (`res_mod`, `obs_mod`, `man_mod`, and `use_mod`). An example of using `get_res` and `old_list` in tandem to loop `gmse_apply` is shown below.

```r
to_scare  <- FALSE;
sim_old   <- gmse_apply(scaring = to_scare, get_res = "Full", stakeholders = 6);
sim_sum_1 <- matrix(data = NA, nrow = 20, ncol = 7);
for(time_step in 1:20){
    sim_new               <- gmse_apply(scaring = to_scare, 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[2];
    sim_sum_1[time_step, 5] <- sim_new$basic_output$manager_results[3];
    sim_sum_1[time_step, 6] <- sum(sim_new$basic_output$user_results[,2]);
    sim_sum_1[time_step, 7] <- sum(sim_new$basic_output$user_results[,3]);
    sim_old                 <- sim_new;
}
colnames(sim_sum_1) <- c("Time", "Pop_size", "Pop_est", "Scare_cost",
                         "Cull_cost", "Scare_count", "Cull_count");
print(sim_sum_1);
```

```
##       Time Pop_size   Pop_est Scare_cost Cull_cost Scare_count Cull_count
##  [1,]    1     1092 1383.2200         NA        10          NA        454
##  [2,]    2      704  634.9206         NA       110          NA         54
##  [3,]    3      724  476.1905         NA       103          NA         54
##  [4,]    4      784  725.6236         NA       105          NA         54
##  [5,]    5      946  793.6508         NA       104          NA         54
##  [6,]    6     1056  997.7324         NA       108          NA         54
##  [7,]    7     1187  997.7324         NA       105          NA         54
##  [8,]    8     1338  997.7324         NA       106          NA         54
##  [9,]    9     1522 1519.2744         NA        10          NA        463
## [10,]   10     1288 1292.5170         NA        10          NA        473
## [11,]   11      943  816.3265         NA       110          NA         54
## [12,]   12     1026 1133.7868         NA        10          NA        455
## [13,]   13      679  657.5964         NA       107          NA         54
## [14,]   14      734  589.5692         NA       110          NA         54
## [15,]   15      823  952.3810         NA       106          NA         54
## [16,]   16      933  793.6508         NA       108          NA         54
## [17,]   17     1078 1043.0839         NA        10          NA        458
## [18,]   18      745 1133.7868         NA        10          NA        460
## [19,]   19      337  362.8118         NA       110          NA         54
## [20,]   20      348  317.4603         NA       110          NA         54
```

Note that one element of the full list `gmse_apply` output is the 'basic_output' itself, which is produced by default when `get_res = "basic"`. This is what is being used to store the output of `sim_new` into `sim_sum_1`. Next, we show how the flexibility of `gmse_apply` can be used to dynamically redefine simulation conditions.

Changing simulation conditions using gmse_apply

We can take advantage of `gmse_apply` to dynamically change parameter values mid-loop. For example, below shows the same code used in the previous example, but with a policy of scaring introduced on time step 10.

```
to_scare  <- FALSE;
sim_old   <- gmse_apply(scaring = to_scare, get_res = "Full", stakeholders = 6);
sim_sum_2 <- matrix(data = NA, nrow = 20, ncol = 7);
for(time_step in 1:20){
    sim_new              <- gmse_apply(scaring = to_scare, 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[2];
    sim_sum_2[time_step, 5] <- sim_new$basic_output$manager_results[3];
    sim_sum_2[time_step, 6] <- sum(sim_new$basic_output$user_results[,2]);
    sim_sum_2[time_step, 7] <- sum(sim_new$basic_output$user_results[,3]);
    sim_old                 <- sim_new;
    if(time_step == 10){
        to_scare <- TRUE;
    }
}
colnames(sim_sum_2) <- c("Time", "Pop_size", "Pop_est", "Scare_cost",
                         "Cull_cost", "Scare_count", "Cull_count");
print(sim_sum_2);
```

```
##       Time Pop_size   Pop_est Scare_cost Cull_cost Scare_count Cull_count
##  [1,]    1     1107  997.7324         NA       106          NA         54
##  [2,]    2     1149 1111.1111         NA        10          NA        461
##  [3,]    3      775  612.2449         NA       110          NA         54
##  [4,]    4      849  748.2993         NA       105          NA         54
##  [5,]    5     1052 1065.7596         NA        10          NA        453
##  [6,]    6      696  861.6780         NA       110          NA         54
##  [7,]    7      776 1043.0839         NA        10          NA        461
##  [8,]    8      383  430.8390         NA       110          NA         54
##  [9,]    9      384  408.1633         NA       107          NA         54
## [10,]   10      390  362.8118         NA       104          NA         54
## [11,]   11      409  702.9478         18       102         232         17
## [12,]   12      470  385.4875         16       101         241         19
## [13,]   13      508  476.1905         22        98         211         12
## [14,]   14      614  657.5964         20        89         231         13
## [15,]   15      725  521.5420         19        91         231         17
## [16,]   16      843 1020.4082         73        10          41        276
## [17,]   17      666  612.2449         14       106         271         19
## [18,]   18      765  929.7052         11       104         307         24
## [19,]   19      873  929.7052         10       110         321         23
## [20,]   20      995  907.0295         23        88         216         10
```

Hence, in addition to the previously explained benefits of the flexible `gmse_apply` function, one particularly useful feature is that we can use it to study change in policy availability – in the above case, what happens when scaring is suddenly introduced as a possible policy option. Similar things can be done, for example, to see how manager or user power changes over time. In the example below, users' budgets increase by 100 every time step, with the manager's budget remaining the same. The consequence of this increasing user budget is higher rates of culling and decreased population size.

```
ub          <- 500;
sim_old     <- gmse_apply(get_res = "Full", stakeholders = 6, user_budget = ub);
sim_sum_3   <- matrix(data = NA, nrow = 20, ncol = 6);
for(time_step in 1:20){
    sim_new               <- gmse_apply(get_res = "Full", old_list = sim_old,
                                        user_budget = ub);
    sim_sum_3[time_step, 1] <- time_step;
    sim_sum_3[time_step, 2] <- sim_new$basic_output$resource_results[1];
    sim_sum_3[time_step, 3] <- sim_new$basic_output$observation_results[1];
    sim_sum_3[time_step, 4] <- sim_new$basic_output$manager_results[3];
    sim_sum_3[time_step, 5] <- sum(sim_new$basic_output$user_results[,3]);
    sim_sum_3[time_step, 6] <- ub;
    sim_old                <- sim_new;
    ub                     <- ub + 100;
}
colnames(sim_sum_3) <- c("Time", "Pop_size", "Pop_est", "Cull_cost", "Cull_count",
                         "User_budget");
print(sim_sum_3);
```

```
##       Time Pop_size   Pop_est Cull_cost Cull_count User_budget
##  [1,]    1     1136 1133.7868        10        300         500
##  [2,]    2      961 1201.8141        10        343         600
##  [3,]    3      717  907.0295       110         36         700
##  [4,]    4      815 1179.1383        10        402         800
##  [5,]    5      532  498.8662       109         48         900
##  [6,]    6      583  680.2721       103         54        1000
##  [7,]    7      617  612.2449       105         60        1100
##  [8,]    8      673  725.6236       103         66        1200
##  [9,]    9      706  634.9206       107         72        1300
## [10,]   10      766  793.6508       100         84        1400
## [11,]   11      817  680.2721       106         84        1500
## [12,]   12      870  975.0567       102         90        1600
## [13,]   13      933  657.5964       109         90        1700
## [14,]   14      986  793.6508       110         96        1800
## [15,]   15     1074 1133.7868        10        682        1900
## [16,]   16      465  453.5147       110        108        2000
## [17,]   17      422  204.0816       106        114        2100
## [18,]   18      372  340.1361       107        120        2200
## [19,]   19      315  294.7846       104        132        2300
## [20,]   20      219  204.0816       105        132        2400
```

There is an important note to make about changing arguments to `gmse_apply` when `old_list` is being used: The function `gmse_apply` is trying to avoid a crash, so `gmse_apply` will accomodate parameter changes by rebuilding data structures if necessary. For example, if the number of stakeholders is changed (and by including an argument such as `stakeholders` to `gmse_apply`, it is assumed that stakeholders are changing even they are not), then a new array of agents will need to be built. If landscape dimensions are changed (or just include the argument `land_dim_1` or `land_dim_2`), then a new landscape willl be built. For most simulation purposes, this will not introduce any undesirable effect on simulation results, but it should be noted and understood when developing models.