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] 1084
##
## $observation_results
## [1] 793.6508
##
## $manager_results
##          resource_type scaring culling castration feeding help_offspring
## policy_1             1      NA      68         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] 90.70295
##
## $manager_results
##          resource_type scaring culling castration feeding help_offspring
## policy_1             1      NA      56         NA      NA             NA
##
## $user_results
##         resource_type scaring culling castration feeding help_offspring
## Manager             1      NA       0         NA      NA             NA
## user_1              1      NA      17         NA      NA             NA
## user_2              1      NA      17         NA      NA             NA
## user_3              1      NA      17         NA      NA             NA
## user_4              1      NA      17         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.

```
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] 1360.544
##
## $manager_results
## [1] 360.5442
##
## $user_results
## [1] 396.5986
```

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).

```
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      64         NA      NA             NA
##
## $user_results
##         resource_type scaring culling castration feeding help_offspring
## Manager             1      NA       0         NA      NA             NA
## user_1              1      NA      15         NA      NA             NA
## user_2              1      NA      15         NA      NA             NA
## user_3              1      NA      15         NA      NA             NA
## user_4              1      NA      15         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.

```
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     1171 1133.7868         NA        10          NA        600
##  [2,]    2      637  385.4875         NA       110          NA         54
##  [3,]    3      680  589.5692         NA       110          NA         54
##  [4,]    4      718  498.8662         NA       110          NA         54
##  [5,]    5      857  975.0567         NA       110          NA         54
##  [6,]    6      950  770.9751         NA       110          NA         54
##  [7,]    7     1068  952.3810         NA       110          NA         54
##  [8,]    8     1225  793.6508         NA       110          NA         54
##  [9,]    9     1374 1292.5170         NA        10          NA        600
## [10,]   10      951  997.7324         NA       110          NA         54
## [11,]   11     1066 1315.1927         NA        10          NA        600
## [12,]   12      564  702.9478         NA       110          NA         54
## [13,]   13      612  566.8934         NA       110          NA         54
## [14,]   14      640  702.9478         NA       110          NA         54
## [15,]   15      718  657.5964         NA       110          NA         54
## [16,]   16      787  861.6780         NA       110          NA         54
## [17,]   17      885  929.7052         NA       110          NA         54
## [18,]   18      998  816.3265         NA       110          NA         54
## [19,]   19     1130  861.6780         NA       110          NA         54
## [20,]   20     1308 1247.1655         NA        10          NA        600
```

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     1150 1224.4898         NA        10          NA        600
##  [2,]    2      628  680.2721         NA       110          NA         54
##  [3,]    3      663  385.4875         NA       110          NA         54
##  [4,]    4      729  589.5692         NA       110          NA         54
##  [5,]    5      874  907.0295         NA       110          NA         54
##  [6,]    6      984 1292.5170         NA        10          NA        600
##  [7,]    7      447  430.8390         NA       110          NA         54
##  [8,]    8      469  521.5420         NA       110          NA         54
##  [9,]    9      513  770.9751         NA       110          NA         54
## [10,]   10      531  521.5420         NA       110          NA         54
## [11,]   11      573  385.4875         10       110         600          0
## [12,]   12      694  498.8662         10       110         600          0
## [13,]   13      824  861.6780         10       110         600          0
## [14,]   14      988  861.6780         10       110         600          0
## [15,]   15     1213 1201.8141         68        10           0        600
## [16,]   16      742  589.5692         10       110         600          0
## [17,]   17      901  952.3810         10       110         600          0
## [18,]   18     1079 1383.2200         55        10           0        600
## [19,]   19      568  498.8662         10       110         600          0
## [20,]   20      689  430.8390         10       110         600          0
```

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.

```r
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     1209 1541.9501        10        300         500
##  [2,]    2     1075 1224.4898        10        360         600
##  [3,]    3      825 1088.4354        10        420         700
##  [4,]    4      482  521.5420       110         42         800
##  [5,]    5      571  702.9478       110         48         900
##  [6,]    6      609  612.2449       110         54        1000
##  [7,]    7      641  544.2177       110         60        1100
##  [8,]    8      664  793.6508       110         60        1200
##  [9,]    9      737  612.2449       110         66        1300
## [10,]   10      767  725.6236       110         72        1400
## [11,]   11      816  839.0023       110         78        1500
## [12,]   12      845  498.8662       110         84        1600
## [13,]   13      911  748.2993       110         90        1700
## [14,]   14      986  861.6780       110         96        1800
## [15,]   15     1066 1020.4082        52        216        1900
## [16,]   16     1040 1043.0839        26        456        2000
## [17,]   17      708  657.5964       110        114        2100
## [18,]   18      710  839.0023       110        120        2200
## [19,]   19      725  725.6236       110        120        2300
## [20,]   20      717  793.6508       110        126        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.

Special considerations for looping with custom sub-models

There are some special considerations that need to be made when using custom sub-models and the `old_list` argument within a loop as above. These considerations boil down to two key points.

1. Custom sub-models *always* need to read in explicitly as an argument in `gmse_apply` (i.e., they will not be remembered by `old_list`).
2. Custom sub-model arguments also *always* need to be updated *outside* of `gmse_apply` before output is used as an argument in `old_list` (i.e., `gmse_apply` cannot know what custom function argument needs to be updated, so this needs to be done manually).

An example below illustrates the above points more clearly. Assume that the custom resource sub-model defined above needs to be integrated with the default observation, manager, and user sub-models using `gmse_apply`.

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

The sub-model can be integrated once using `gmse_apply` as demonstrated above, but in the full `gmse_apply` output, the argument `X` will not change from its initial value (because sub-model functions can take any number of arbitrary arguments, `gmse_apply` has no way of knowing that `X` is meant to be the resource number and not some other parameter).

```
sim_4 <- gmse_apply(res_mod = alt_res, X = 1000, get_res = "Full");
print(sim_4$basic_output);
```

```
## $resource_results
## [1] 1500
##
## $observation_results
## [1] 1519.274
##
## $manager_results
##          resource_type scaring culling castration feeding help_offspring
## policy_1             1      NA      67         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 above output, the resource abundance has increased and is now `sim_4$basic_output$resource_results`. But if we look at `sim_4$X`, the value is still 1000.

```
print(sim_4$X);
```

```
## [1] 1000
```

To loop through multiple time steps with the custom function `alt_res`, it is therefore necessary to update `sim4$X` with the updated value from either `sim4$resource_vector` or `sim4$basic_output$resource_results` (the two values should be identical). The loop below shows a simple example.

```
init_abun   <- 1000;
sim_old     <- gmse_apply(get_res = "Full", res_mod = alt_res, X = init_abun);
for(time_step in 1:20){
    sim_new               <- gmse_apply(res_mod = alt_res, get_res = "Full",
                                        old_list = sim_old);
    sim_old               <- sim_new;
    sim_old$X             <- sim_new$resource_vector;
}
```

Note again that the custom sub-model is read into to `gmse_apply` as an argument within the loop (`res_mod = alt_res`), and the output of `sim_new` is used to update the custom argument `X` in `alt_res` (`sim_old$X <- sim_new$resource_vector`). The population quickly increases to near carrying capacity, which can be summarised by using the same table structure explained above.

```
init_abun   <- 1000;
sim_old     <- gmse_apply(get_res = "Full", res_mod = alt_res, X = init_abun);
sim_sum_4   <- matrix(data = NA, nrow = 5, ncol = 5);
for(time_step in 1:5){
    sim_new                 <- gmse_apply(res_mod = alt_res, get_res = "Full",
                                          old_list = sim_old);
    sim_sum_4[time_step, 1] <- time_step;
    sim_sum_4[time_step, 2] <- sim_new$basic_output$resource_results[1];
    sim_sum_4[time_step, 3] <- sim_new$basic_output$observation_results[1];
    sim_sum_4[time_step, 4] <- sim_new$basic_output$manager_results[3];
    sim_sum_4[time_step, 5] <- sum(sim_new$basic_output$user_results[,3]);
    sim_old                 <- sim_new;
    sim_old$X               <- sim_new$resource_vector;
}
colnames(sim_sum_4) <- c("Time", "Pop_size", "Pop_est", "Cull_cost",
                         "Cull_count");
print(sim_sum_4);
```

```
##      Time Pop_size  Pop_est Cull_cost Cull_count
## [1,]    1     1500 1473.923        10        400
## [2,]    2     1875 1836.735        10        400
## [3,]    3     1992 1882.086        10        400
## [4,]    4     1999 2222.222        10        400
## [5,]    5     1999 2086.168        10        400
```

This is the recommended way to loop custom functions in `gmse_apply`. Note that elements of `old_list` will over-ride custom arguments to `gmse_apply` so **specifying custom arguments that are already present in `old_list` will not work**.