

BEE-STEWARD: Manual

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To run the BEE-STEWARD model you need to install the free, open source software NetLogo version 5.3.1: <https://ccl.northwestern.edu/netlogo/5.3.1/>

Make sure the BEE-STEWARD folder is unzipped and all input files are in the same folder as the program.

**This manual has been updated for use with BEE-STEWARD version 2.0. When using the model, please cite the original publication and the version you are using.**

**Original model citation:**

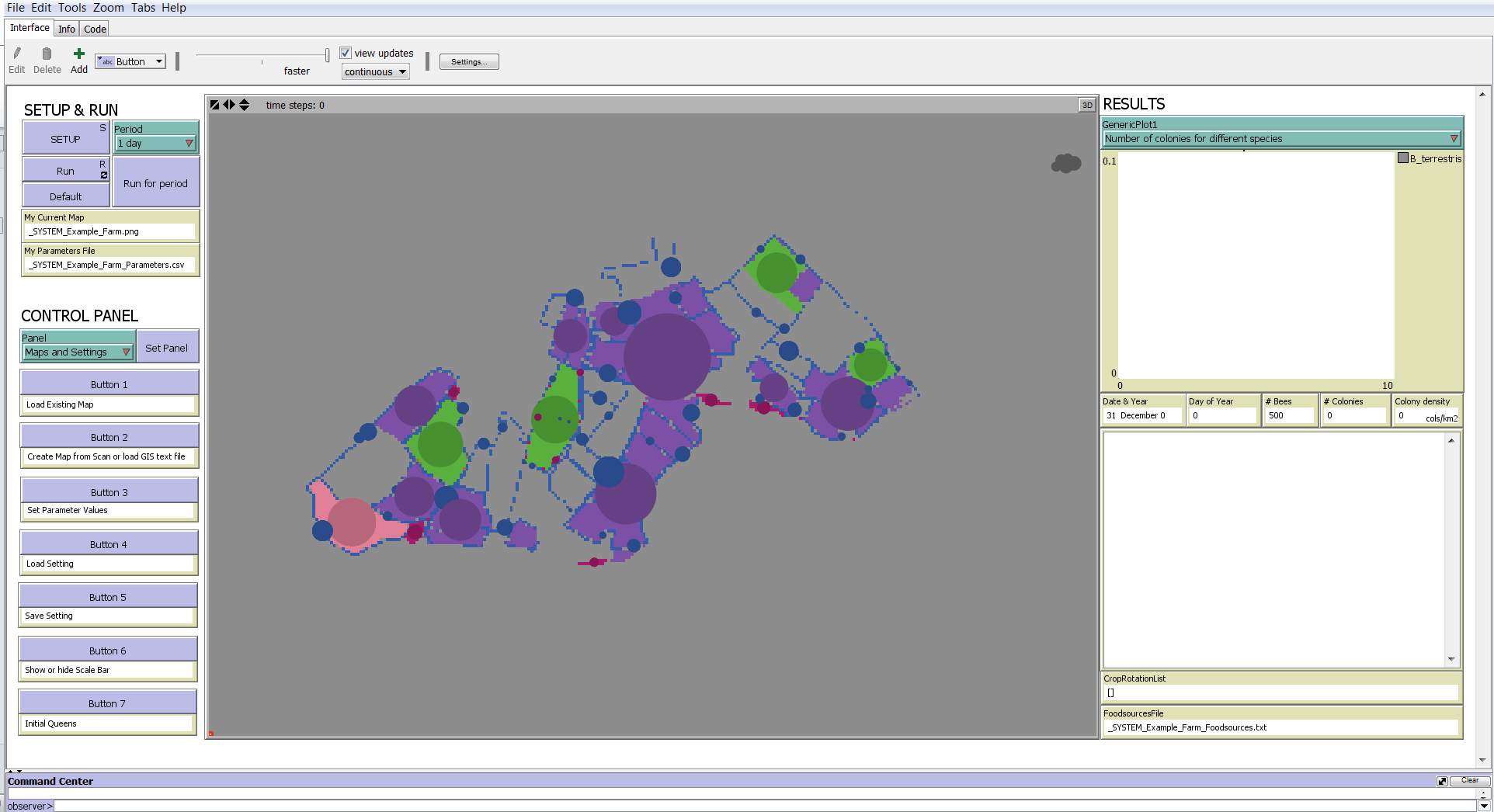
[Twiston-Davies, G., Becher, M. A., Osborne, J. L. (2021) BEE-STEWARD: a research and decision-support software for effective land management to promote bumblebee populations. Methods Eco Evol, 12: 1809-1815.](https://besjournals.onlinelibrary.wiley.com/doi/epdf/10.1111/2041-210X.13673)

**BEE-STEWARDv2.0 citation:**

Twiston-Davies, G., Shaw, R.F., Comont, R.F., Becher, M.A. (2023) BEE-STEWARDv2.0 Landscape scale and extended habitats. Software tool.  DOI: 10.5281/zenodo.8370020

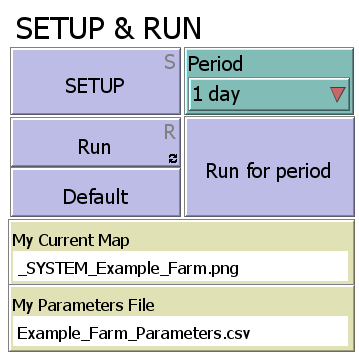
# I. OVERVIEW INTERFACE

Note the BEE-STEWARDv2 Example Farm looks a bit different, but all the processes are the same.



## Setup

1.) To run the model under default setting, press "SETUP" and "Run" or choose a "Period" and "Run for period".

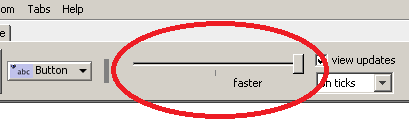


When a button is selected it will turn from blue to black.



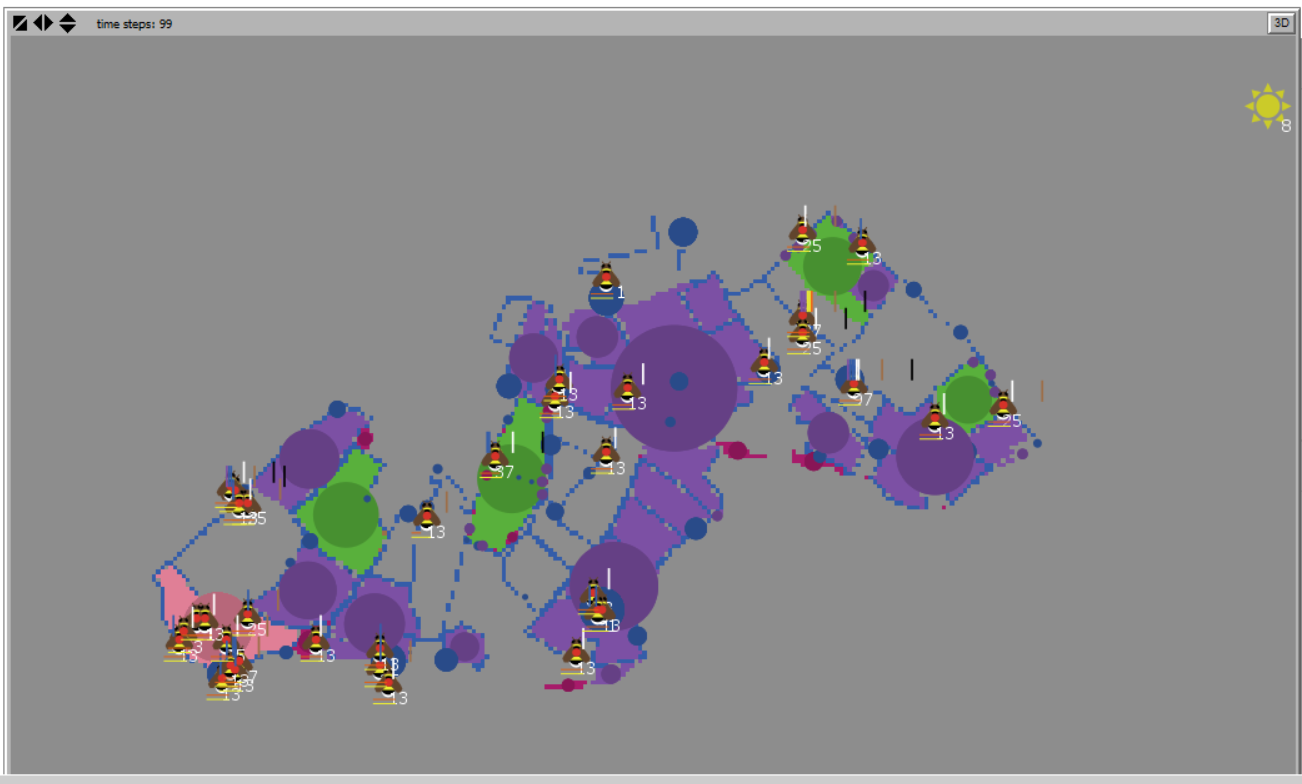
Press the "Default" button to set all parameters to their default value, loading the "SYSTEM" files.

To increase the running speed of the model, move the NetLogo speed slider to the right:



## The World

2) The simulated "world" shows locations of food sources and bumblebee colonies as well as colony structures and stores.

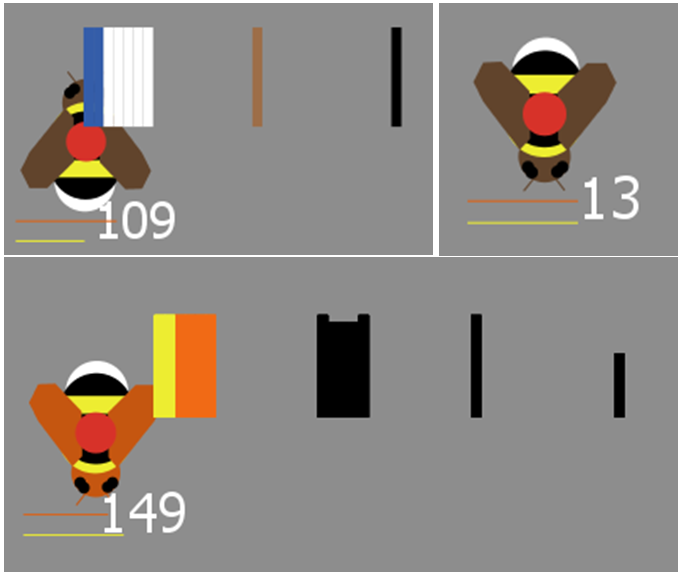


Food sources are shown as circles:



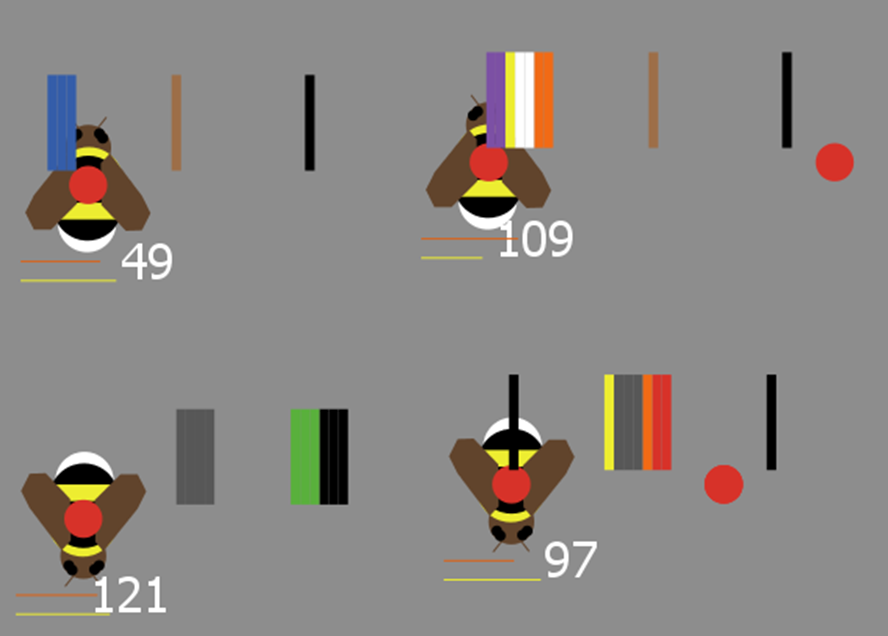
The maize field is represented by a green circle.

Colonies are shown as bumblebees:



Adult queens are shown as red circles (mother queens on the "thorax" of their colony). Each (vertical) bar represents a cohort of bees, with the size of the bar reflecting the number of bees (in "cohort-based colonies" this number is constant (= 12 bees)). Colonies are shown upside down once they reached their competition point and no more eggs can be produced. "Individual-based colonies", where each single bee is an individual agent, are shown with orange wings and head (Note: in the default setting, all colonies are "cohort-based". To add "individual-based" colonies, set COLONIES\_IBM to an integer > 0 (see Step 1 (3.): "Change parameter setting")).

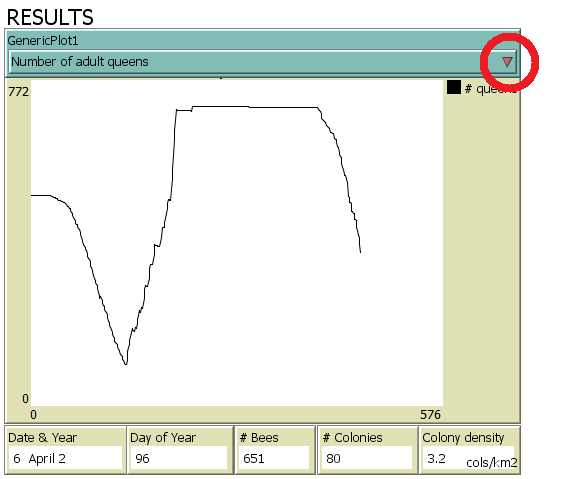
The horizontal bars below the colony show the pollen (orange) and nectar (yellow) stores of the colony, relative to the colony's need for nectar and pollen. The number in the bottom right corner (the colony's label) shows the total colony size (including brood) (to show other colony statistics, see Step 5 "Display options").



Blue bars are diploid, female (or male) eggs, white bars are diploid larvae, brown bars are worker (or diploid male) pupae, black bars are adult workers. Purple bars are haploid, male eggs, yellow bars are haploid, male larvae, grey bars are haploid, male pupae and green bars are haploid (or diploid) male adults. Orange bars are queen destined larvae, red bars queen pupae (red circles away from a colony are hibernating queens). Diploid male brood follows the same colour schemes as diploid worker brood but diploid adult males are shown in green (if "SexLocus?" is true).

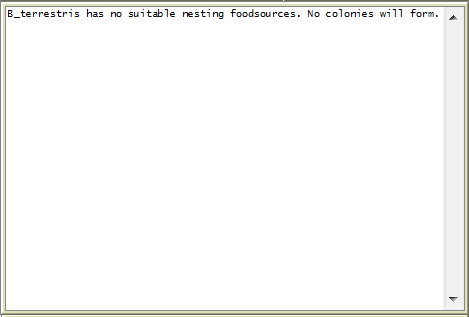
## Plots

There are five monitors, showing today's date and year, the day of the year, number of adult bees (workers, queens, males), number of colonies and colony density and a graph, plotting a certain result, chosen by the user, over time. Output options for the plot are (click red triangle): "Number of colonies", "Number of adult queens", "Colony structures", "Food available", "Number of colonies for different species" and "Species total adult queens"



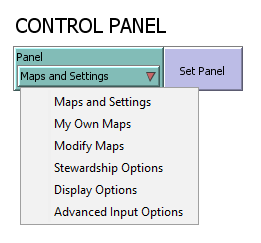
## Output

The output window may show additional information for the user. This could be notifications by the model (e.g. "B\_terrestris has no suitable nesting habitat"). It can also be used to display e.g. the model parameters and their current value.



## Control Panel

Use the buttons of the control panel to load, modify or save maps, change your settings etc. There are six different panel setting, which can be chosen via the "Panel" chooser (click the red triangle, select and press the "Set Panel" button):



# II. HOW TO USE BEE-STEWARD

The BEE-STEWARD tool uses the bumblebee population model Bumble-BEEHAVE to simulate the development of bumblebee populations or communities in a given landscape. It integrates the map defining modules of the landscape model BEESCOUT, to allow the user to easily create new or modify existing maps. Typically, when using BEE-STEWARD, you first create a new map (e.g. from an image file), then you define the bee, landscape and display setting and then run the model, using the "Setup" and "Run" buttons with the results being displayed by the plot and monitors on the right side of the interface. You can then modify the map, e.g. by applying stewardship options, and run the model again. For more experienced users there are also options to run a large set of simulations automatically (see Step 7: BehaviorSpace).

## BEE-STEWARD Files

The program comes with a number of default example files ("\_SYSTEM\_") which should not be changed by the user. The files required by the model are:

1.) the actual BEE-STEWARD model, implemented in Netlogo: **\_BEE-STEWARD\_Model.nlogo** ".

2.) an input file defining bumblebee species: "\_SYSTEM\_BumbleSpecies\_UK\_01.csv"

3.) an input file defining forage flower species: "\_SYSTEM\_Flowerspecies.csv"

4.) an input file defining the habitat types (and the colours): "\_SYSTEM\_Habitats.csv"

These four files are typically not changed by the user (but see Step 8 for defining new habitats).

There are also some "Project" files, which can be created and modified by the user (or automatically by the model itself):

5.) an image (".png") file, defining the map used in this project. The name of the map is set by the user, e.g. "MyProject.png" (The default example map is "\_SYSTEM\_Example\_Farm.png")

*Alternatively - only recommended for advanced users - a map can also be defined by a text file (example file: "\_SYSTEM\_Textmap\_Sussex1.txt* ")(see Step 8)

6.) an input text file (".txt"), defining the food sources (default example: "\_SYSTEM\_Example\_Farm\_Foodsources.txt"). This file is automatically created and named by the model. The file name is composed of the name of the image map loaded and the suffix "\_Foodsources" (e.g. "MyProject\_Foodsources.txt").

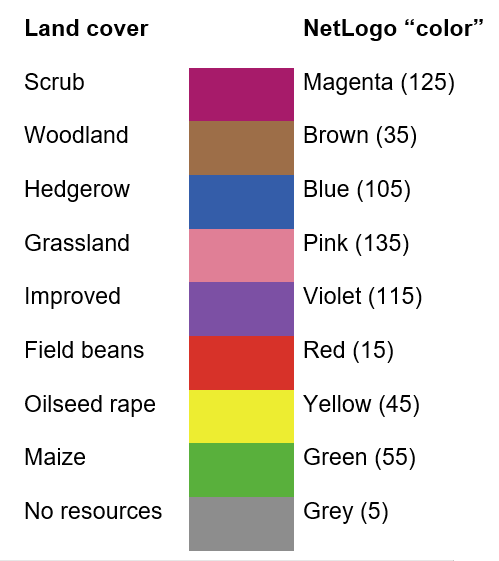
7.) an input file (".csv") defining the parameterisation for the current project. This can be for example the number of initial queens or various display options (default: "\_SYSTEM\_Parameters.csv").

## Step 1: Creating a new map

### 1.) Preparing the image file

You first need to create the actual map, i.e. an image file where different colours represent the different habitat and crop types. There are two easy ways do this: Either by scanning a physical map, where different habitat and crop types are shown in different colours. Supported image file formats are: "bmp", "jpg", "gif", and "png", but "png" is preferable. You may want to use an image editing program (e.g. Photoshop or the free software tool Gimp) to improve the quality of the image. Alternatively, you can draw your own map, using the BEE-STEWARD tools. This is explained in step 3: "Draw or modify a map".

You can follow the BEE-STEWARD default colour scheme when creating your first map:



To create maps in GIS or define new habitat or crop types or change colours, see Step 8 (Advanced User's Guide).

More advanced users can define their colour scheme with an unlimited number of habitat types (see Step 8).

Tips for creating BEE-STEWARD maps:

A large number of very small food patches can distract scouting bees in the model from bigger, more profitable food sources and may have a negative impact on the bee population. In the default setting, food sources offering less than a minimum of nectar and pollen are hence removed (*MinSizeFoodSources?* = true; *RemoveEmptyFoodSources?* = true) and hedges, which tend to be small due to their linear structure, can be merged into a single, larger patch (*MergeHedges?* = true).

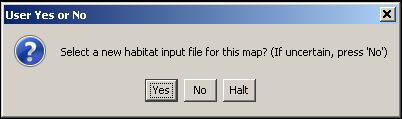
To minimise the impact of these adjustments, we suggest to avoid having very small patches on the map. Also, double-check that no artifacts are created when Netlogo imports a new image file (these are usually one or a few pixels of a different colour, often at the border of two neighbouring habitats).

Note that while we have made more habitats available we recommend that you limit yourself to one or two habitats for each major type of habitats. For example you may have a mix of improved grassland, permanent pasture and rush pasture on your farm. We recommend using only one of two habitat types that are the majority and record all fields as either, for example, improved grass or permanent pasture.

### 2.) Load the image file

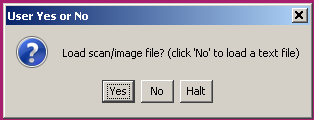
Set "Panel" to "Maps & Settings" (press "Set Panel" to apply) and press the button "Create Map from Scan or load GIS text file".

A user dialogue pops up, asking about the habitat file to be used:



**Press "No"** (unless you have specifically created a new habitat input file for this map before, see step 8)

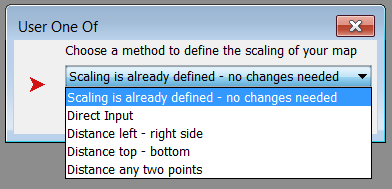
Another user dialogue asks for the type of input file used:



**Press "Yes"** (unless you have created a text input file for this map in GIS, see Step 8)

Select and open the image file you have prepared. The file is then loaded, which may take a moment.

You are then asked to define the scale of your map:



Choose **"Scaling is already defined"** if you have defined the scale of this map already. Otherwise, select one of the four remaining options:

"**Direct Input**" if you already know the scaling, choose this option and provide the scaling as the real edge length [m] of a grid cell in the model

**"Distance left - right side"** if you know the real distance between the left and the right side of your map (don't choose this option, if there is a magenta bar on the left and right side)

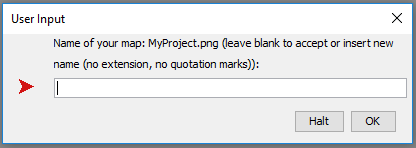
**"Distance top - bottom"** if you know the real distance between the top and the bottom of your map (don't choose this option, if there is a magenta bar on the top and bottom)

**"Distance any two points"** if you know the real distance of two clearly identifiable points on the map (e.g. beginning and end of a scale bar)

Press "OK". If you chose "Distance any two points", you are asked to select the points via two (left) mouse clicks. Make sure, the NetLogo speed slider is set to "normal" before clicking on the map. Selected points are marked red. Once you chose two points, you are asked, if you are happy with the location of the two points or if you want to repeat point selection and whether the colour of the marker points needs to be changed. Repeat, until you are happy with the location of the two points, then select "Yes - continue" and press "OK".

Now provide the real distance (in metres), press "OK".

Set NetLogo speed slider to maximum to speed things up and wait, until the landscape is completely analysed by the model.

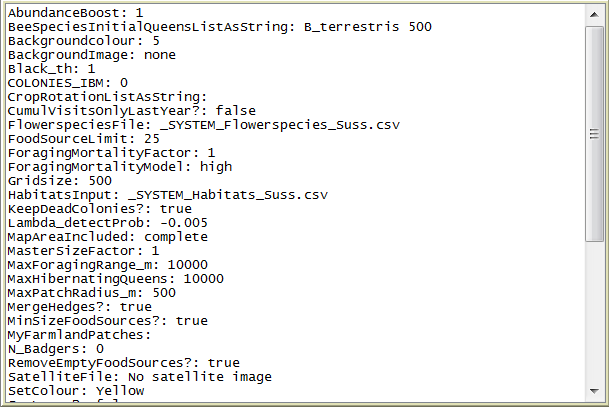


Provide a new name (or leave blank to accept suggested name). The image map will then be saved in the "png" format.

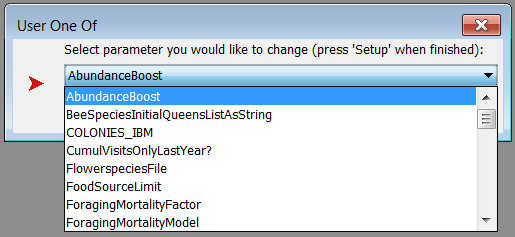
The model is ready to run, as soon as Button 2 ("Create Map from Scan or load GIS text file") has turned grey again. The model has now created a new foodsources file and a parameters file, both linked to the image map (in "png" format).

### 3.) Change parameter settings

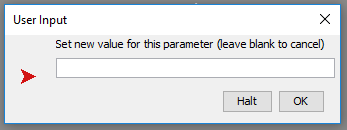
When a new project is created under default settings, a new parameter file is created as a copy of "\_SYSTEM\_Parameters.csv". This means for example, that the initial number of bees is set to 500 *Bombus terrestris* queens. The button "Set Parameter Values" (Button 3, Panel "Maps and Settings") allows the user to change these settings. Pressing the button, lists all parameters and their current value in the output window:



It also opens a user dialogue, listing those model parameters defined in the "\_Parameters.csv" file that can be changed by the user.



Choose the parameter you wish to change and press "OK".



Then insert the new value and press "OK". The project's parameter file is then updated and saved. Make sure the value you enter is in the right format and makes sense! Finally, **press** "**SETUP**" before you run the model again.

Settings can also be imported from other projects via the button "Load Setting" (Button 4, Panel "Maps and Settings"). When loading the file "\_SYSTEM\_Parameters.csv", the default parameterisation for this project is restored.

Settings can also be saved via the button "Save Setting" (Button 5, Panel "Maps and Settings").

## Step 2: Save or Load a Project

### 4.) Load Existing Projects

To load a previously created map, press button "Load Existing Map" (Button 1, Panel "Maps and Settings") and select a file that belongs to the project you would like to load.

If you have a larger number of projects, it may be convenient to have your favourite ones ready to be loaded with one mouse click. To do this, switch Panel to "My Own Maps". The first button loads a default map ("\_SYSTEM\_Sussex1.png"), buttons 2 - 6 are not linked to a project yet (there is no file name shown within the parentheses) and can be defined by the user.

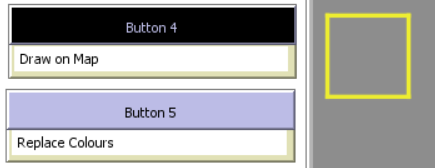
First, load a map/project you would like to save (e.g. via the button "Load Existing Map" on Panel "Maps and Settings"), then press one of the still undefined (i.e. empty parenthesis) "Load Map" buttons. Now, the map name of your current project appears in the parenthesis of the button, and when you press this button again in future, this project will be loaded.

To delete the link of a "Load Map" button with its project, press button "Delete one of My Maps" (Button 7, Panel "My Own Maps"), select the button you would like to clear in the user dialogue and press "OK".

## Step 3: Draw or modify a map

### 5.) Draw a new map or modify an existing one

To draw a new map from scratch, switch to the panel "Modify Maps" and press "Clear whole Map" (Button 6). To modify an existing map, avoid clearing the map. Before you "Draw on Map" (Button 4), make sure the speed slider is set to normal. You remain in the drawing mode, while the mouse pointer is hovering over the map. The shape, size and colour of the brush is visualised:

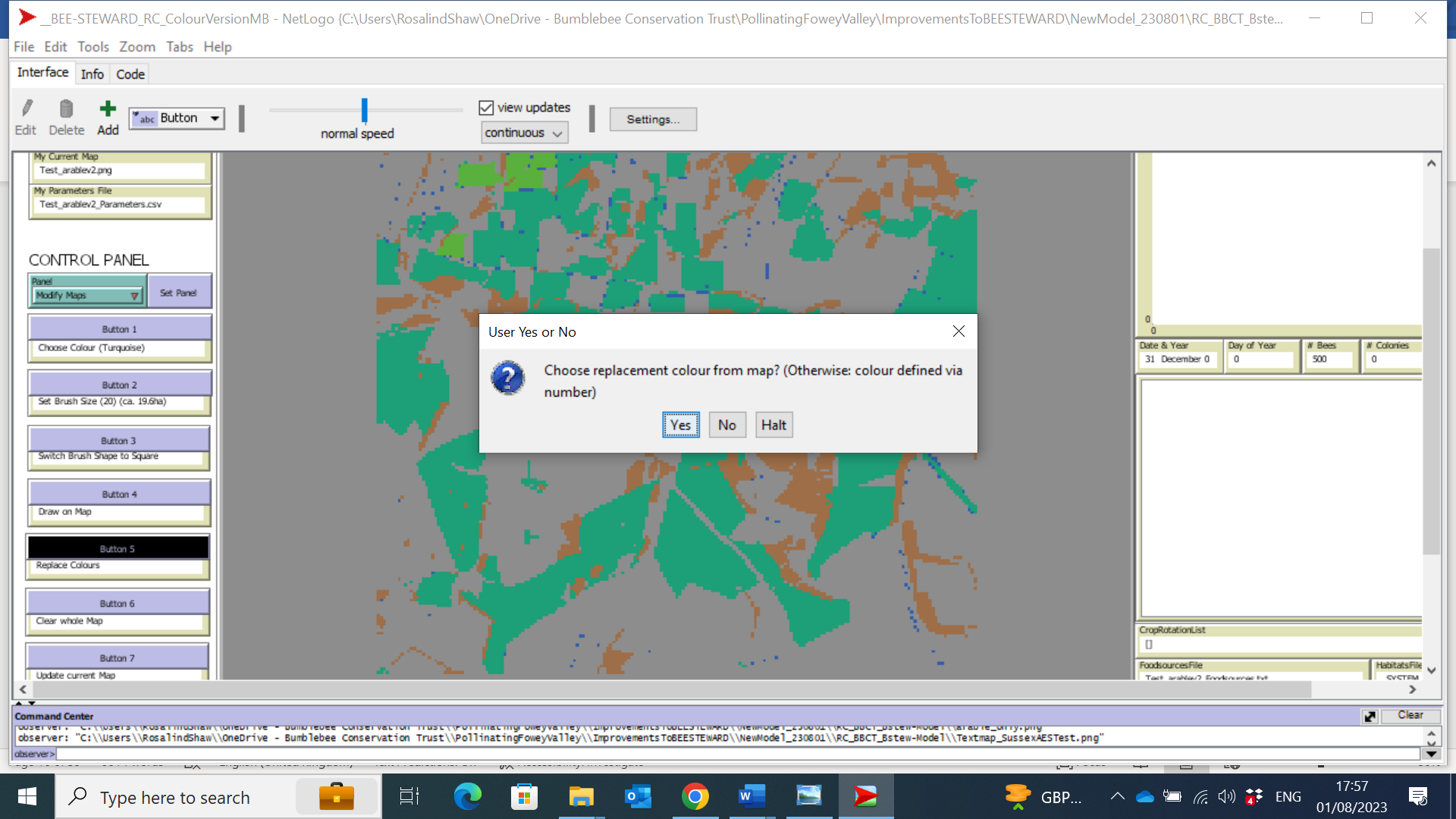


To change the brush settings, press "Choose colour (*current colour*)" (Button 1), "Set Brush Size (*current value*)(*approx. area*)" (Button 2) or "Switch Brush Size to *Circular/Rectangular*" (Button 3).

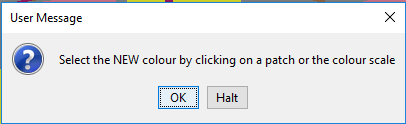
Use the colour "Grey" to delete habitats. Use "Restore" to selectively delete newly added changes and restore the original map in the covered areas.

"Replace Colours" (Button 5) first asks if you wish to choose replacement colour from map. If the colour exists on the map or is one of the 13 ‘primary’ BEE-STEWARD colours, select ‘Yes’.

If your habitat is one of the lighter or darker net logo (e.g. lightred, darkred), we recommend you select ‘No’ and input the Netlogo color as a number (you find this in the \_SYSTEM\_Habitats file column ‘habitatColourID’)

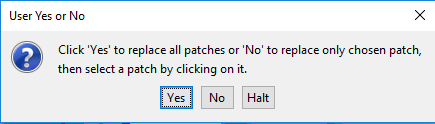


If you select yes, it temporarily adds two colour scales of NetLogo ‘color swatches’ to the very left and right side of the map. A user dialogue then pops up:



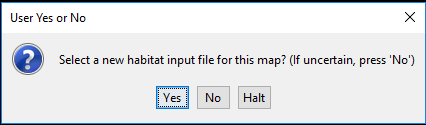
Click "OK" and then click either on the map or on the colour scale to select your new colour.

When you have selected your new colour, either by clicking on the map or colour scale or by entering the Netlogo colour number, another user dialogue appears:



Choose your option and then click on the specific patch (or habitat type) you want to change. If your choice was "Yes" (replace all patches) then all patches of the selected habitat type change their colour to the previously chosen new colour. If your choice was "No" (replace only one patch) then only the patch you have selected changes its colour.

Finally, press "Update Current Map" (Button 7) (and set speed slider to maximal speed) to reanalyse the map and create the updated input files. You are asked to set a name for the new map, then you have the option to choose a habitat input file different from the default habitat file:



Click "No" unless you want to use a habitat file you have previously created (e.g. to have more or different habitat options than in the default file - see step 8 (Advanced User's Guide)).

You are then asked again about the scaling (choose "Scaling is already defined" if you have modified an existing map).

## Step 4: Stewardship options

### 6.) Applying hedgerow stewardship options

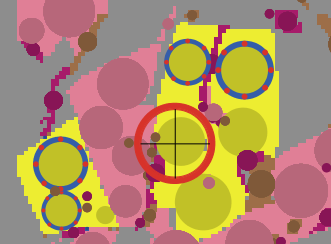
The baseline hedgerow is now an annually cut hedgerow with occasional flowering willow trees (based on the original BEE-HAVE hedgerow data, with information on the flowering density of hedges cut annually in autumn from Staley et al. 2020, see Appendix A), colour blue. There is a replacement habitat based on an autumn cut hedge cut every three years (or a third of the hedge cut every year, Staley et al. 2020). Replace all hedges on the farm with this habitat, rather than trying to specify individual hedges. Use "Modify Maps" Button 5 Replace colours. Select orange as the colour. When asked if all patches should be replaced, click yes.

**NOTE 1:** we recommend you update the hedgerow option before adding any other Stewardship option, as otherwise they may not be recorded.

**NOTE 2:** there are two habitats now called ‘Hedgerow’ with different colours (blue and orange) in the \_SYSTEM\_Habitats file. This may cause problems when using exporting pollen and nectar values. If issues are occurring, start a fresh version of the model, with only the Hedgerow habitat you prefer in the \_SYSTEMS\_Habitats file in the correct colour for your map.

### 7.) Select fields to apply a stewardship option

Switch to the panel "Stewardship Options", set speed slider to "normal" and press "Select Field" (Button 2), once selected the Button will turn black. Immediately move your mouse pointer to the NetLogo “World” where your map is and you can select one or more crop fields (i.e. the circles representing a food source in the model, not the patches of the underlying map) with a single left mouse click. If the “Select Field” button turns back to blue before you have selected your field then click it again, this may happen if you hover your mouse pointer over the “CONTROL PANEL” for an extended time without moving your mouse pointer to the NetLogo “World” or when you move your mouse pointer back to the “CONTROL PANEL”. Note: only crop fields and not semi-natural habitat patches can be selected. Selected fields are then surrounded by a blue circle with red dots. Click again to unselect or press "Unselect all Fields" (Button 6) to unselect all fields.



Move the mouse pointer outside of the NetLogo world to end the selection mode.

### 8.) Select and apply stewardship options

BEE-STEWARDv2.0 has been updated with more Stewardship options. Please note that hedgerow management or entire field-based stewardship options are applied as a whole habitat via the ‘Replace colours’ function (see Section 6 above). There are now six potential Stewardship options which can be applied as ‘legume’, ‘margin’ or ‘plot’. Legume options are a proxy for a sown legume fallow, and replace the entire food source patch, and are based on Delaney (2018). Currently both legume options are the same. Two ‘margin’ types are available: ‘Margin’ based on a flower rich margin which contains a mix of flower species and grass (based on Holden (2022)); ‘BirdBumble\_Margin’ based on a mix aimed at both wild bird overwinter seed resources and pollinator friendly flowers (based on Ouvrard & Jacquemart (2018)). Two ’plot’ types are available: ‘Plot’ based on a Nectar and pollen rich plot (Shaw et al in prep) and Game\_cover\_Plot (based on a mix designed for wild bird cover including some pollinator friendly species such as *Brassica* spp, sunflowers and phacelia; Holden (2022)). While the ‘Plots’ and ‘margins’ are applied differently in terms of information entered (see below), if you wish to apply the ‘Plot’ type habitat as a margin, simply calculate the area of your margin by hand and add as below.

Very small margins are not incorporated well into the model and may cause negative effects; for most we recommend a minimum margin size of 5m x 500m and for mixes aimed partly at bird conservation we recommend minimum sizes of -

Game\_cover\_Plot type: minimum plot size of 2 ha

BirdBumble margin: minimum plot size of 0.75 ha i.e. 10m x 750 m margin

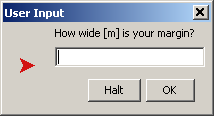
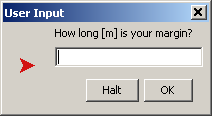
For details of the habitats and how they relate to current AES schemes see Appendix A.

The precise number of flowers for these options will depend on the seed mix, soil type, slope, management and region etc., so users are encouraged to edit these values in the habitat input file to their circumstances for more accurate predictions.

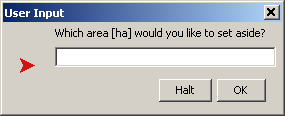
Press "Apply Stewardship" (Button 3). Depending on the chosen stewardship option, more user input might be required:

**legume**: no additional input required

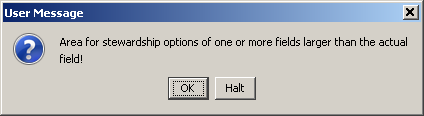
**margin**: provide the width [m] of the margin and the proportion [0..1] of the field's circumference that is covered by the margin.

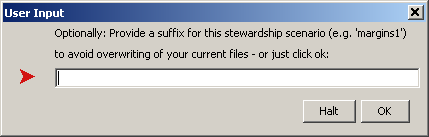
**plot**: provide the area [ha] that is set aside.



If the area of a margin or a plot is larger than that of a selected field, a warning is issued and the area of the stewardship option is set to the area of the field.



Finally, provide a a suffix (e.g. *legume*) to avoid overwriting of the input files. Set speed slider to maximal speed. Creating the new input files may take a moment, so wait while “Apply Stewardship” (Button 3) remains black.



Note that the chosen stewardship option and specifications is applied to all the fields selected. To apply different stewardship options to different fields, repeat the process, select a second set of fields and apply another stewardship option.

Oilseed rape field with stewardship options:

legume: margin: plot:

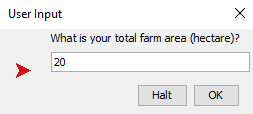


Only one stewardship option can be applied to a single field. If a field with a stewardship option already being applied is selected, the stewardship option will be removed, when "Apply Stewardship" (Button 3) is pressed. Stewardship options cannot be applied to semi-natural habitats.

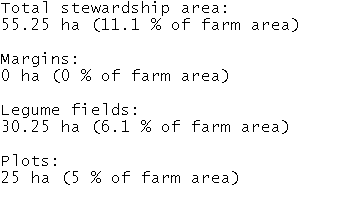
Three oilseed rape fields with stewardship options are selected, to remove the stewardship options click “Unselect all Fields” (Button 6).



To see the total amount (and percentage) of stewardship areas for a farm, press "Show Stewardship Areas" (Button 4) and provide the total area [ha] of the farm



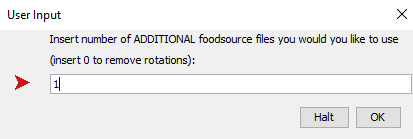
The results are shown in the output window:



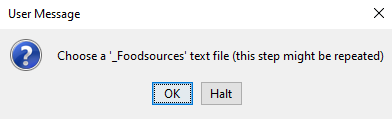
### 9.) Crop rotations

If crops on one or more fields or patches of semi-natural habitat change from one year to another, the model can use two or more different "\_Foodsource" input files. These files must be based on the same map and have to be created first (see "Step 3").

Press "Define Crop Rotation" (Button 5) and insert the number of *additional* input files (0 results in the removal of crop rotation):



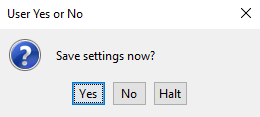
Then select the food source input file that is going to be used in year 2 (and year 4, 6, etc. in case of two food source input files):



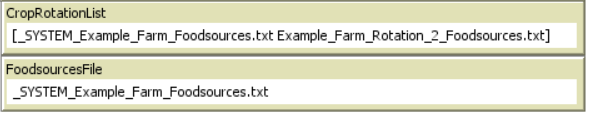
If you loaded the Default "\_SYSTEM\_Example\_Farm.png" map you can select " Example\_Farm\_Rotation\_2\_Foodsources.txt" as your food source file for the second year.

Selecting new foodsources files is repeated as specified by the user in the previous input. Note. You must only select foodsources files, if you select any other file type then your rotation swill not run.

Finally, save the new setting/crop rotation:



The foodsource input files and their order are saved in the variable "CropRotationList" and shown - together with the current food source input file - below the output window:

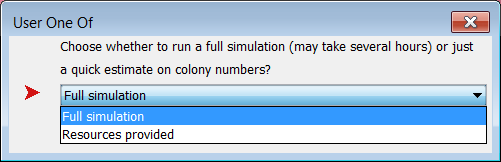


Please note that adding rotations does not change the image of the map, but foodsources (shown as circles) may change their colour from one year to the next. It is also possible to have more or fewer patches or fields from one year to another.

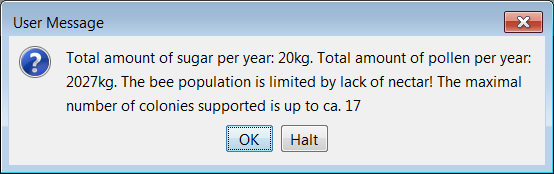
### 10.) Run simulations and create your BEE-STEWARD report

There are report options - an instant assessment ("Quick estimate") of the number supported colonies, based on the total amount of nectar and pollen available during one year in the landscape. The number of colonies is based on average consumption rates of bumblebees (Rotheray *et al.* 2017, J Apic Res, Vol. 56, No. 3, 288–299) and does not reflect the spatial or temporal distribution of the food sources, or any other biological processes. Alternatively, a BEE-STEWARD simulation is run repeatedly (20 times) over five simulated years to determine the average model outcome ("Full Simulation"). However, this process may take several hours depending on the size and quality of the landscape.

Press "Generate My Report!" (Button 7), and select the type of report you would like to generate:

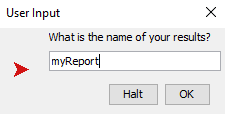


For "Resources Provided", a message pops up with the amount of nectar and pollen provided and calculated number of supported colonies and whether the bumblebee population in this landscape is likely limited by pollen or by nectar (example):

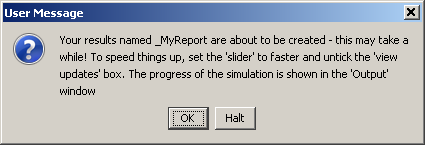


If the map contains a high proportion of mass-flowering crops like oilseed rape, the number of colonies is likely overestimated.

To run a "Full simulation", first provide a name for your result file:



A user-message pops up:



Then the simulations are run automatically and a result .csv file is created. You can now repeat the simulation with a modified map to create a second result file. To compare the results, open the Excel file "\_SYSTEM\_My BEE-STEWARD Report.xlsm", press the button (press Enable Content if prompted) "Create my report PDF" and select the two result files you have created (these will have “\_” at the beginning of them e.g. “\_MyReport.csv”), a PDF comparing your results will be automatically created.

# III. ADVANCED OPTIONS

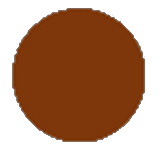
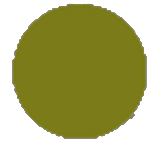
## Step 5: Display options

### 11.) Choose which elements are displayed

Select the panel "Display Options" and press "Default view" (Button 1) to return to the default display setting.

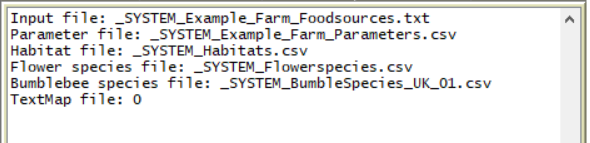
Press "Show Nectar Visits" (Button 2) or "Show Pollen Visits" (Button 3) to visualise the relative number of nectar and pollen visits in each food patch, with light colours representing more visits than the average patch and dark colours less visits. Visualisation of visits is only updated directly after pressing the button and not automatically while the model is running. Note. "Show Nectar Visits" (Button 2) or "Show Pollen Visits" (Button 3) will only work after you have run a simulation, for a simple demonstration choose from the SETUP & RUN panel “Period”, select “1 year” from the dropdown menu and then click on “Run for period”, once the simulation has run, select “Display Options” from the “CONTROL PANEL”, click on “Set Panel” and click on “Show Nectar Visits” (Button 2).

Colours of a patch with an average number of nectar (left) and pollen (right) visits:

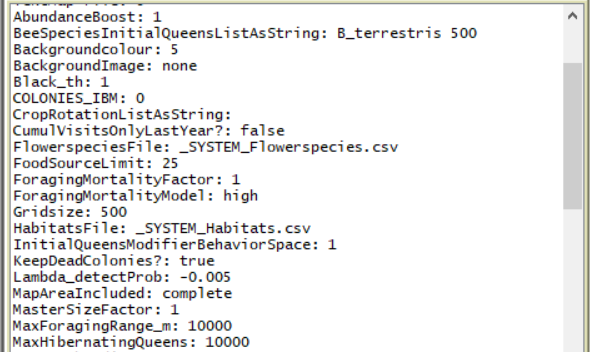


Use the "Identify!" (Button 4) option to identify elements on the map (e.g. habitat types) while hovering over them with the mouse pointer (set speed slider to "normal"). A left mouse click on the element then opens the NetLogo agent monitor to provide further information.

"Show Input Files" (Button 5) lists all input files in the output window.



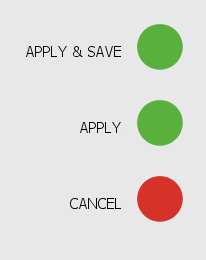
"Show Parameter Values" (Button 6) lists the current parameter setting in the output window:



"More Display Options" (Button 7) allows the user to select which "agents" (e.g. bees, food sources etc.) are shown.



Red "buttons" are turned on (i.e. the element is shown), grey buttons are turned off.



Finally press the virtual "Apply & Save" button to apply the setting and save it to the parameter file, just "Apply" it without saving or "Cancel" to neither apply nor save the setting.

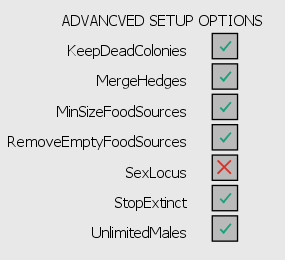
## Step 6: Advanced input options

### 12.) Quickly change some parameter settings

Select panel "Advanced Input Options".

Press **"Set Random Seed (*current value*)"** (**Button 1**) to change the random seed. This value determines the sequence of pseudo-random numbers used to simulate stochasticity in the model. If it is set to a value larger than 0, then re-running the model with the same random seed and unchanged parameter settings will result in the same results. If it is set to 0, the current real time and date is used to initialize the random-number generator and the results of a run will not be (exactly) reproducible.

Press **"Advanced Setup Options" (Button 2)** to set some of the boolean parameters:



Again, press "Apply & Save", "Apply" or "Cancel" to set and return to the normal display.

**"Add a Background Image" (Button 3)** replaces the display of the underlying map by an image chosen by the user e.g. satellite image of the mapped area.

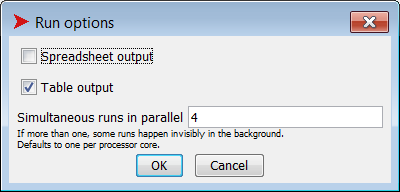
## Step 7: BehaviorSpace

To run a large set of simulation, use the NetLogo tool "BehaviorSpace" (NetLogo Tools/BehaviorSpace) (see <http://ccl.northwestern.edu/netlogo/5.3.1/docs/behaviorspace.html>).

Please note that BehaviorSpace normally requires those parameters that are tested to be defined on the user interface. However, with a few exceptions, most parameter values in BEE-STEWARD are read in from a "parameter" file. To make sure, BehaviorSpace works correctly with BEE-STEWARD, you have to set the global variable "**BehaviourSpaceParameters**" in BehaviorSpace and list all those parameters that vary or are set to values other than their default value (as defined in "\_SYSTEM\_Parameters.csv") - *with the exception of* **"MyMap"** and **"RAND\_SEED"**, which are defined in the standard way. Furthermore, "**BeeSpeciesInitialQueensListAsString**" (e.g. set to "B\_terrestris 500") and "**CropRotationListAsString**" (e.g. set to "") need to be listed und "Vary variables...".

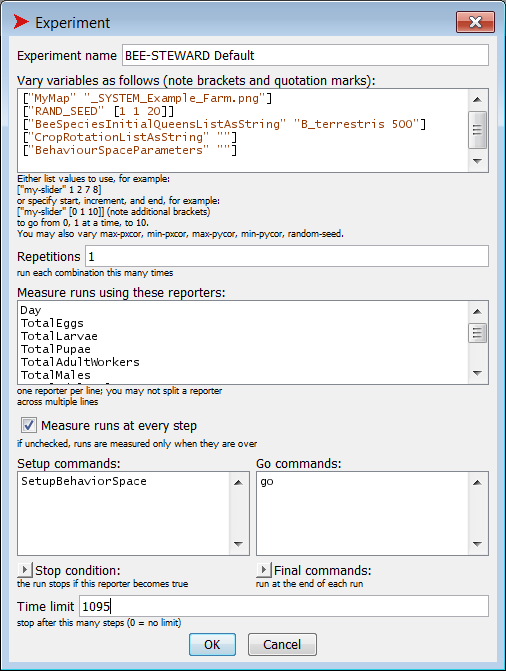
Also it is essential to call "**SetupBehaviorSpace**" under "Setup commands" and *not* "Setup".

The following examples are already listed as experiments when opening BehaviorSpace. An example of the simulations that we carry out in the manuscript is also included called “BEE-STEWARD Manuscript Experiment”. To set up new experiments, we recommend to "Duplicate" an existing experiment and to modify it. To run a BehaviorSpace experiment you have set it up, press "OK", then select it and click "Run". When asked for the "Run options" we recommend using "Table output" instead of "Spreadsheet output":



Depending on the size and quality of the map, the number of runs and time steps, and the number of cores available on your computer, a BehaviorSpace experiment may take a long time. Make sure the speed slider is to its maximum and "Update view" and "Update plots and monitors" are unticked.

**Example 1: Default setting**



"Vary variables as follows.." is set to:

["MyMap" "\_SYSTEM\_Example\_Farm.png"]

["RAND\_SEED" [1 1 20]]

["BeeSpeciesInitialQueensListAsString" "B\_terrestris 500"]

["CropRotationListAsString" ""]

["BehaviourSpaceParameters" ""]

This means: The simulation runs on the default example farm map with 20 replicates (the first value in the bracket indicates the start value, the second the increment and the last the final value. An alternative notation would be ["RAND\_SEED" 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20]). Although "BeeSpeciesInitialQueensListAsString" does not deviate from the default setting, it needs to be listed here, as well as "CropRotationListAsString" and "BehaviourSpaceParameters", which are both set to "" (i.e. quotations marks without a blank), as no changes to the default setting are made.

To run simulations with another (single) bee species or another (but constant) initial number of queens, replace the species name or the number accordingly, e.g. ["BeeSpeciesInitialQueensListAsString" "B\_lapidarius 250"] would create 250 initial *B. lapidarius* queens instead of 500 *B. terrestris* queens (make sure you use exactly the same spelling for each bee species as it is defined in the bee species input file ("\_SYSTEM\_BumbleSpecies\_UK\_01.csv")).

Make sure that whenever you run a BehaviorSpace experiment that at least these five parameters ("MyMap", "RAND\_SEED", " BeeSpeciesInitialQueensListAsString", "CropRotationListAsString" and "BehaviourSpaceParameters") are listed.

Leave "Repetitions" at 1 as replicates are dealt with via "RAND\_SEED".

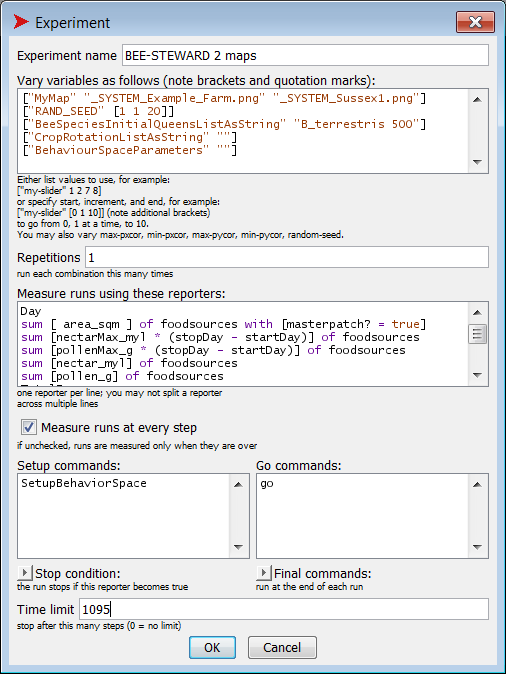
"Measure runs using these reporters" defines which output is generated. An overview of the most useful options is provided at the end of this chapter (see also BehaviorSpace example "BEE-STEWARD VariousOutput").

If "Measure runs at every time step" is ticked, then the results of each time step are recorded (measure is recorded at each day of the simulation), which may result in extremely large output files. If it is unticked, results are only recorded at the end of each run (see e.g. BehaviorSpace example "BEE-STEWARD SmallerOutputFile").

"Setup commands": Make sure it says " SetupBehaviorSpace" here (and not just "Setup").

"Time limit" defines the number of time steps and is set to 1095 (3 years) in this example.

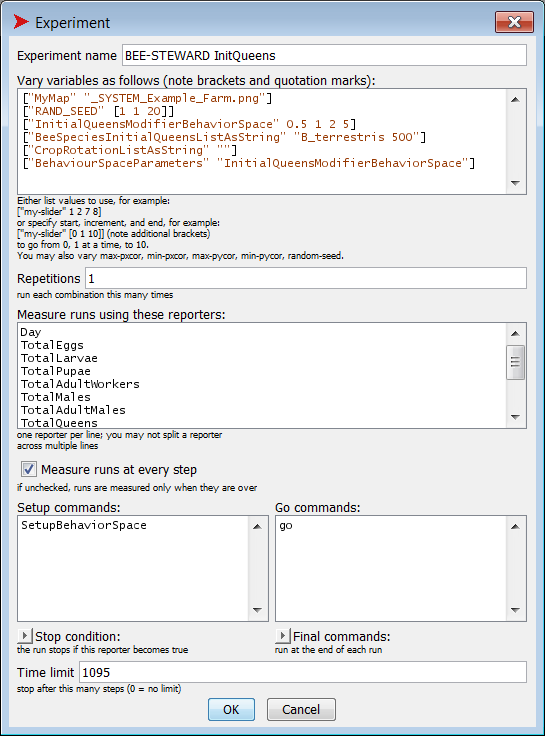
**Example 2: Two maps**



In contrast to the first example, the simulations now run on *two* different maps, "\_SYSTEM\_Example\_Farm.png" and "\_SYSTEM\_Sussex1.png". Again, the number of replicates is 20 and hence 40 simulations are run altogether. There are no other deviations from the default setting, hence BehaviourSpaceParameters is again set to "".

As this example tests two different maps, additional output is listed on "Measure runs using these reporters" addressing e.g. the area of forage habitat and nectar and pollen production.

**Example 3: Varying initial bee numbers**

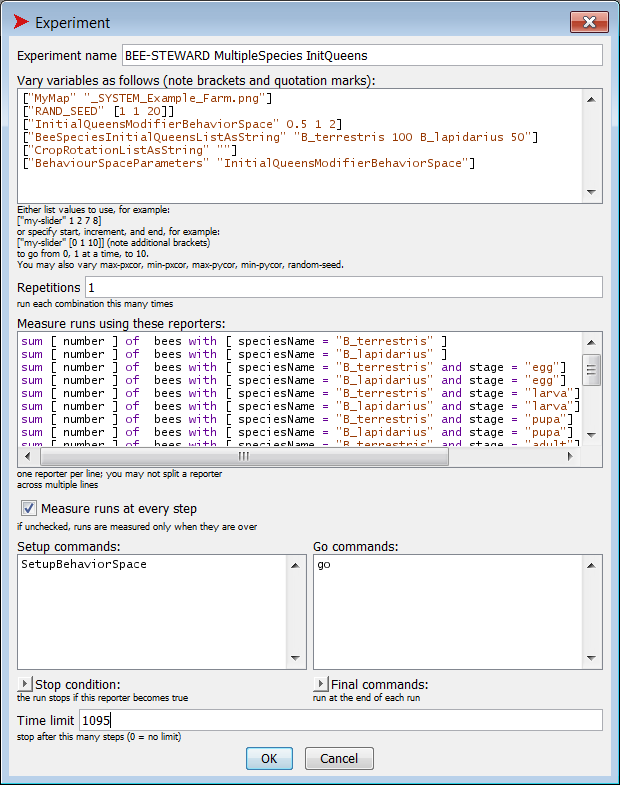


This simulation only runs on the default farm example map, but now the initial number of *B. terrestris* queens varies and is set to "InitialQueensModifierBehaviorSpace" times 500 (rounded!).

So the initial number of *B. terrestris* queens will be 250, 500, 1000 and 2500. The total number of runs is 4 x 20 = 80.

As "InitialQueensModifierBehaviorSpace" is defined via the parameter file (set to 1 per default), it needs to be listed: ["BehaviourSpaceParameters" "InitialQueensModifierBehaviorSpace"]. (Leaving "BehaviourSpaceParameters" at "" would result in 80 simulation runs, *always* starting with 500 initial queens).

**Example 4: Varying bee species and initial numbers**

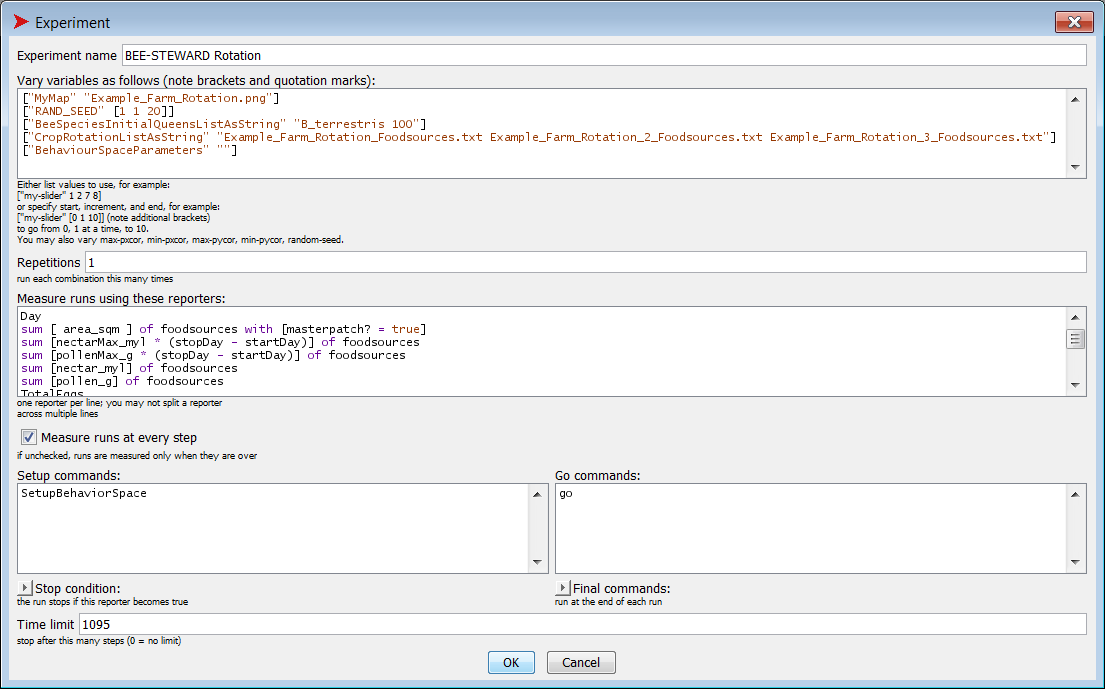


Like in example 3, "InitialQueensModifierBehaviorSpace" is varied (and hence listed under "BehaviourSpaceParameters"). However, this simulation also runs with two different bee species, being present at the same time. "InitialQueensModifierBehaviorSpace" is applied to both initial queen numbers, hence the ratio of initial queens of 2:1 (*B. terrestris* to *B. lapidarius*) is maintained. This means that simulation runs will be with 50 *terrestris* and 25 *lapidarius* or with 100 *terrestris* and 50 *lapidarius* etc. To change these ratios (e.g. having the same numbers of initial queens in both species) or running simulations for both species but with only one species being present at a time, a new BehaviorSpace experiment would have to be set up.

Please also note that common output variables like "TotalAdultWorkers" etc. do not distinguish between different bee species. Hence, the output listed in "Measure runs using these reporters" differs here from the previous examples and explicitly ask for the numbers in each bee species.

The total number of simulation runs in this experiment is 20 x 3 x 2 = 120.

**Example 5: Crop rotation**



This example simulation is a variation of the "Default" example. However, crop rotations are now defined, resulting in an update of the map/foodsources after each year. To do this, "CropRotationsListAsString" needs to be set from "" to e.g. if run for 10 years "Example\_Farm\_Rotation\_Foodsources.txt Example\_Farm\_Rotation\_2\_Foodsources.txt Example\_Farm\_Rotation\_3\_Foodsources.txt ". Hence, in the years 1, 4, 7,10 etc. "Example\_Farm\_Rotation\_Foodsources.txt" is used as input file, in the years 2, 5, 8 etc. " Example\_Farm\_Rotation\_2\_Foodsources.txt” and in the years 3, 6, 9 etc. " Example\_Farm\_Rotation\_3\_Foodsources.txt " is used (if simulation is run for multiple rotation periods such as for 10 years). The number and input files in a crop rotation system can be changed, however, it is not possible to compare two or more rotation systems with each other in a single BehaviorSpace experiment. To do such a comparison, you have to set up a new experiment for each system. (E.g. "Duplicate" this experiment, re-name it "BEE-STEWARD Rotation2" and set "CropRotationsListAsString" to " Example\_Farm\_Rotation\_Foodsources.txt Example\_Farm\_Rotation\_2\_Foodsources.txt Example\_Farm\_Rotation\_4\_Foodsources.txt " (make sure Example\_Farm\_Rotation\_4\_Foodsources.txt has been created first!)

**Useful Output Options**

(Please note that most of these variables do not distinguish between different bee species. Variables called "Total..." refer to the current time step and hence are usually 0, if output is only created at the end of a simulation runs (i.e. usually at the end of a year when all bees left are hibernating queens).

**Day**: The day of the year, i.e. 1-365 (in contrast to the in-built "step" output, which is the time step)

**TotalActiveBees**: today's number of bees which can (potentially) perform a task, i.e. adult workers and adult queens, which are not in hibernation and still alive.

**TotalEggs**: the number of all eggs present today

**TotalLarvae**: the number of all larvae present today

**TotalPupae**: the number of all pupae present today

**TotalAdultWorkers**: the number of all adult workers present today

**TotalMales**: the number of all bees with caste = "male" (eggs, larvae, pupae or adults) present today

**TotalAdultMales**: the number of all adult males present today

**TotalQueens**: the number of all bees with caste = "queen" present today (i.e. females, which are (destined to become) queens (older larvae, pupae or adults, mother or daughter queens)

**TotalAdultQueens**: the number of all adult queens (mothers and daughters) present today

**TotalUnmatedQueens**: the number of bees with caste = "queen" and mated? = false present today

**TotalHibernatingQueens**: the number of queens in hibernation present today

**TotalAdults**: the number of all adult bees present today

**TotalColonies**: the number of colonies present today

**TotalAdultMalesEverProduced**: the sum of all males that have ever reached adulthood

**TotalAdultQueensEverProduced**: the sum of all queens that have ever reached adulthood

**TotalAdultsEverProduced**: the sum of all bees that have ever reached adulthood

**TotalBeesEverProduced**: the sum of all eggs that have been laid

**TotalColoniesEverProduced**: the sum of all colonies that have ever been produced

**TotalForagingTripsToday**: the number of all foraging trips today

sum [ area\_sqm ] of foodsources with [masterpatch? = true]: the area of forage habitat [m2] on the map

sum [nectarMax\_myl \* (stopDay - startDay)] of foodsources: the total amount of nectar [ul] produced in this landscape during one year

sum [pollenMax\_g \* (stopDay - startDay)] of foodsources: the total amount of pollen [g] produced in this landscape during one year

sum [nectar\_myl] of foodsources: the total amount of nectar [ul] available today

sum [pollen\_g] of foodsources: the total amount of pollen [g] available today

**PopulationSizeDay365List**: lists the total number of bees present at 1st January of each year. This is particularly useful, if simulations run for several years and "Measure runs at every time step" is *not* ticked

**TimeToExtinction**: If a population goes extinct, "TimeToExtinction" is set to the time step, when it happened (otherwise it is 0). This is particularly useful, if simulations run for several years and "Measure runs at every time step" is *not* ticked

## Step 8: Advanced User's Guide

**CUSTOMIZE INTERFACE**

**Add more Plots:**

- right click white are of interface, add "plot"

- leave plot name at "plot 2" (or 3...5 for further plots)

- tick "Show legend?"

- delete default plot pen

- set Y max to 0.1

- right click white area of interface, add "chooser" and call it "GenericPlot2" (or 3..5)

- copy and paste all or a selection of the following options to the chooser's "Choices" (include the quotation marks) and press OK:

"Total eggs"

"Total adults"

" Number of adult queens"

"Hibernating queens"

"Colony structures"

"Biomass (dw) [kg]"

"Tongue lengths workers (histogram)"

"Tongue lengths queens (histogram)"

"Bee weights [mg] (histogram)"

"Age distributions bee agents (histogram)"

"Sex ratio"

"Matrilines (histogram)"

"Genepool (histogram)"

"Number of colonies"

"Colony sizes (histogram)"

"Stores: nectar [ml] & pollen [g]"

"Foraging period max. [hrs]"

"Foraging trips daily"

"Foodsources sizes (histogram)"

"Food available"

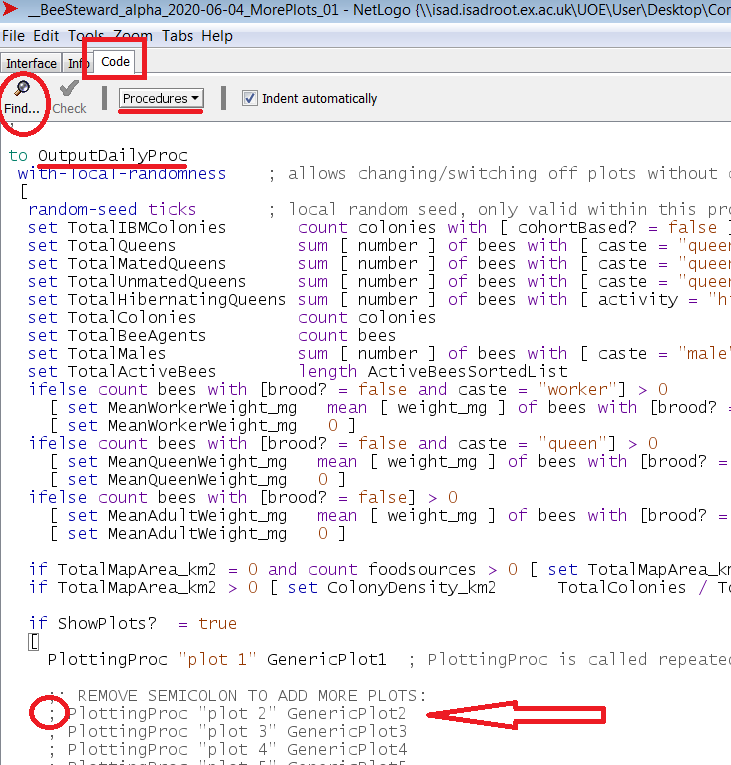
"Species total adults"

"Species total adult queens"

"Species hibernating queens"

"Number of colonies for different species"

Switch to the NetLogo "Code" tab and move down to "OutputDailyProc" (either using "Procedures" or "Find.." "GenericPlot2"). Delete the semicolon in front of the command "PlottingProc "plot 2" GenericPlot2" and "Save" the updated model version. The new plot will now show, whatever has been selected via its associated chooser.



### Define new habitats

Open "\_SYSTEM\_Habitats.csv" and create a copy under a new name. Each line represents a habitat type. Please note, in order to allow for a large number of habitats, the format of the habitat type has been changed in comparison to BEESCOUT 2.0.

Habitats are defined by:

habitatColourID (column 1): a colour value following the NetLogo colour scheme (see figure below). E.g. in the default setting, Oilseed rape is 45 (yellow). As colours may vary when a map is loaded from an image file, a colour range needs to be provided (e.g. colourRangeMin: 43, colourRangeMax: 45).

habitatSwitchedOn? (column 4) is a boolean variable (true or false) and defines whether this habitat type is considered as being present or not.

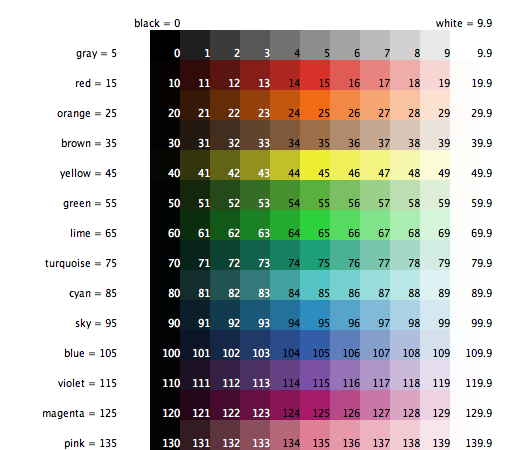
habitatType (column 5) is the name of the habitat (e.g. " Crop\_Oilseed\_rape")

Column 6 ("ONLY FLOWER DATA BEYOND THIS COLUMN!") needs to be "n/a"

Each of the following columns defines the abundance (number of flowers/m2) of the flower species listed.

The phenology, nectar and pollen production etc. of each flower species is defined in "\_SYSTEM\_Flowerspecies.csv"

The NetLogo “Color swatch”



To add a new habitat type, provide the required information in a new line to the habitat file and save. To apply this file, click "Yes" when asked "Select a new habitat input file for this map?" (see Step 5) and select this file.

If necessary, you can also add new columns with new flowers. Make sure, you also provide the definition of these flower species in "\_SYSTEM\_Flowerspecies.csv" (We recommend to keep a copy of the original "\_SYSTEM\_Flowerspecies.csv"!).

For more detailed information and guidance see SI.6 Manual\_using\_GIS\_maps\_for\_BEE-STEWARD.

### Preparing the map in GIS

If you are familiar with a GIS program, you can create a map either as an image or as a text file. Best results are achieved when the image file has the same dimensions as the BEE-STEWARD world, i.e. 300x210 pixels.

Maps can also be defined by a text file, which follows the Arc GIS ASCII format, e.g.:

ncols 201

nrows 201

xllcorner 533986.76120021

yllcorner 109997.20296882

cellsize 25

NODATA\_value -9999

-9999 -9999 ... -9999 -9999

-9999 5 5 ... 5 5 -9999

-9999 5 5 ... 5 5 -9999

...

-9999 135 135 ... 5 5 -9999

-9999 -9999 ... -9999 -9999

The first line defines the number of columns (no more than 310), the second line the number of rows (no more than 210). The actual real world x and y coordinates of the origin (lower left corner) of the map are given by xllcorner and yllcorner, cellsize gives the dimensions of a grid cell [m], the "no data value" is -9999.

The following lines define the map, where each number represents a NetLogo colour (e.g. 5 is grey, 135 is pink). If the map has less than 308 columns, the first and last column should be made up of NODATA\_values (-9999) (see "\_SYSTEM\_Textmap\_Sussex1.txt" as an example). This ASCII file will be produced automatically when you convert a raster map based on the NetLogo colours to ASCII in ArcGIS for example. You then simply need to convert this to a ext (.txt) file by opening up the file in Notepad or equivalent program and saving as a .txt file

For more detailed information and guidance see SI.6 Manual\_using\_GIS\_maps\_for\_BEE-STEWARD.

# Appendix A – Details of new habitats added to BEE-STEWARD v2

| **Habitat** | **Source** | **Comment** |
| --- | --- | --- |
| **Original habitats** |  |  |
| Crop\_Cereals | Becher et al. (2018) |  |
| Crop\_Field\_beans | Becher et al. (2018) |  |
| Crop\_Maize | Becher et al. (2018) |  |
| Crop\_Oilseed\_rape | Becher et al. (2018) |  |
| Grass\_Improved | Becher et al. (2018) | Note renamed from ‘Improved’ to place in grassland category. Not referred to as grassland as bumblebees can now nest in grassland habitats, but it is unlikely that they can nest in temporary leys |
| Grassland | Becher et al. (2018) | Note that this is a good quality semi-natural grassland, is more favourable to bumblebees then the Wildflower meadow habitat added below. |
| Scrub | Becher et al. (2018) |  |
| Woodland | Becher et al. (2018) |  |
| **New habitats** |  |  |
| Heath | Shaw et al. (in prep) | Lowland heath |
| Hedgerow | Staley et al. (2020) | The baseline hedge is now an annually cut hedge, cut in autumn, with occasional standard willow trees. Hedge basal flora and willow values taken from Becher et al. 2018, combined with woody species information from Staley et al (2020). |
| Hedgerow\_tri\_cut | Staley et al. (2020) | This is a triennially cut hedge, cut in autumn to a standard height. Woody species values take from Staley et al. (2020), combned with hedge basal flora and willow values from taken from Becher et al. (2018) |
| Orchard |  | Estimate of 50 blossoms per m2 during flowering. |
| Permanent\_pasture | Shaw et al. (in prep) | Permanent grazed land |
| Permanent\_pasture\_GS2 | Shaw et al. (in prep) | Permanent grazed land under the relaxed grazing option (GS2) |
| Rush pasture | Shaw et al. (in prep) | Grazed land dominated by soft or hard rushes. |
| Traditional orchard | Shaw et al. (in prep) | Traditional apple orchard with grassland in orchard managed for lowland meadow restoration |
| Wetland mosaic | Shaw et al. (in prep) | A low intensity grazing or ungrazed habitat around watercourses consisting of wetland herbs and scrub. |
| Wildflower meadow | Shaw et al. (in prep) | Grassland managed for grassland restoration to lowland hay meadow incorporating once/twice annual cuts with limited/no grazing during summer. |
| Woodland\_mixed | Becher et al. (2018) | The original BEE-STEWARD woodland provides a large amount of resources, so this habitat is reduced to represent a mixed woodland. Note we recommend you choose one type of woodland. |
| **New agri-environemnt schemes – note can only have one new margin, one new plot, one new legume.** | | |
| FlowerSpeciesList\_Legume | Delaney (2020) | Estimated change to a grass/legume based mix, based on data collected on AB15 Sown legume fallow, left for 2 years without grazing or fertiliser, GS4. This habitat is also included as a separate habitat type ‘Legume\_3’ for pollen and nectar analyses. |
| FlowerSpeciesList\_Margin | Holden (2022) Pollen and nectar margins | Similar to AB8 Flower-rich margins and plots. This includes both wildflowers and grasses, and is more similar to a wildflower meadow mix. This habitat is also included as a separate habitat type ‘Flower\_margin’ for pollen and nectar analyses. |
| FlowerSpeciesList\_Plot | Shaw et al (in prep) | Similar to AB1 Nectar flower mix, containing predominantly insect pollinated plants. This habitat is also included as a separate habitat type ‘Nectar\_plot’ for pollen and nectar analyses. |
| FlowerSpeciesList\_newCSO\_Legume |  | Currently contains the Legume data as above – can be altered to other ‘replacement’ habitat. |
| FlowerSpeciesList\_newCSO\_Margin  BirdBumble\_Margin | Ouvrard & Jacquemart (2018) | Similar to AB16: winter bird /bumble mix.  This habitat is also included as a separate habitat type ‘BirdBumble\_mix’ for pollen and nectar analyses. |
| FlowerSpeciesList\_newCSO\_Plot  GameCover\_Plot | Holden (2022) | Similar to AB9: Wild bird mix including buckwheat, phacelia, sunflower. This habitat is also included as a separate habitat type ‘GameCover\_Plot\_57’ for pollen and nectar analyses. |

**Reference list for full habitats and flowers used in BEE-STEWARD version 2**

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