INTRODUCTION

Bumblebees provide vital pollination services for crop production and wildflowers (Klein et al., 2007; Ollerton et al., 2011). However, their numbers are declining, with land-use change resulting in the reduction of flower-rich habitat being one of the main drivers (Baude et al., 2016; Vanbergen et al., 2013). Land management interventions that enhance bumblebee forage and nesting site availability, offer mitigation options across farmed landscapes, for example, Agri-environment schemes (European Commission, 2020). These interventions can increase some bumblebee reproductive success measures in agriculturally intensive areas (Carvell et al., 2011, 2015). Still, their impact on long-term bumblebee population survival is unclear and the effect of cropping patterns over multiple years are rarely considered.

APPLICATION

BEE-STEWARD: A research and decision-support software for effective land management to promote bumblebee populations

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Abstract

1. The demand for agent-based models to explore the effects of environmental change on pollinator population dynamics is growing. However, models need a simple yet flexible interface to enable adoption by a wide range of stakeholders.
2. We introduce BEE-STEWARD: a research and decision-support software tool, enabling researchers, policymakers, land management advisors and practitioners to predict and compare the effects of bee-friendly management interventions on bumblebee populations over several years.
3. BEE-STEWARD integrates the BEESCOUT and Bumble-BEEHAVE agent-based models of bumblebee behaviour, colony growth and landscape exploration into a user-friendly interface, with reconstructed code, and expanded functionality. Bespoke automatic reports can be created to illustrate how different land management interventions can affect the densities of bumblebees and their colonies over time.
4. BEE-STEWARD could be an important virtual test bed for scientists exploring the impacts of different stressors on bumblebees and used by those with little or no modelling experience, enabling a shared methodology between research, policy and practice.

KEYWORDS
agent-based modelling, BEESCOUT, Bombus terrestris, Bumble-BEEHAVE, individual-based modelling, pollinator, systems model
The demand for agent-based models to explore the effects of environmental change on pollinator population dynamics is growing, and mechanistic models can be used to simulate long-term population trends and the impact of stressors and mitigation measures (Becher et al., 2013; EFSA, 2015; E.P.A., 2015; Henry et al., 2017). With Bumble-BEEHAVE (Becher et al., 2018) and its landscape module BEESCOUT (Becher et al., 2016), powerful agent-based models exist to predict the impact of land use on bumblebee behaviour, colony growth and population dynamics. However, these models were built for researchers, so interpretation and implementation of results for decision-making is limited (Kerr, 2004). Models need a simple yet flexible interface to enable adoption by a wide range of research, policy and practice users. It is only through stakeholder consultation during model development (Rossi et al., 2014) that this implementation barrier to evidence-based land management could be overcome (Dicks et al., 2014).

We have therefore, created BEE-STEWARD (Figure 1), integrating Bumble-BEEHAVE and BEESCOUT into a research and decision-support software tool, enabling researchers, land management advisors and practitioners to predict and compare the effects of bee-friendly interventions on bumblebee populations (colony sizes, numbers and survival) over several years. While the underlying model processes are validated and unchanged (Becher et al., 2016, 2018), the code has been reconstructed, some previous limitations removed, new functionality created and a user-friendly interface has been redesigned.

2 | THE BEE-STEWARD SOFTWARE TOOL

2.1 | Development

Stakeholder consultation is an essential practice in developing decision-support tools (Rossi et al., 2014). Therefore, BEE-STEWARD functionality and interface have been co-designed and refined through workshops and pilots with bumblebee researchers and key land advisory and management stakeholders to widen the potential end-users beyond academia.

Our stakeholder consultation process highlighted that to guide decision-making, a software tool needed to be (a) user-friendly and straightforward whilst (b) also reflecting realistic landscape management options process; findings also supported by Rose et al. (2016). We, therefore, firstly integrated the landscape exploration module of BEESCOUT into Bumble-BEEHAVE for ease of loading, creating, modifying and running habitat maps with the bumblebee model in one application (see SI.3 user manual for how this was coded via the Dryad Digital Repository or the Supporting Information). Secondly, we reconstructed the code for a simplified interface (Figure 1) by designing a generic control panel displaying a subset of functions at any one time, providing a step-by-step approach. Thirdly, we expanded functionality by creating features relevant to real-life decision-making and created a bespoke automatic report function to visualise how different land management interventions can affect the densities of bumblebees and their colonies over time. The report

![Figure 1](image-url)
function provided a simple alternative to assess intervention options’ impact without applying more advanced model analysis tools (e.g. NetLogo’s ‘BehaviorSpace’ or statistical software, which are still researcher options).

2.2 | Model description

BEE-STEWARD (Figure 2) was implemented and runs in the NetLogo (version 5.3.1; Wilensky, 1999) freeware which can be downloaded here: https://ccl.northwestern.edu/netlogo/5.3.1/. The BEE-STEWARD tool and all system files it needs to run can be found as Data Files downloadable via the Dryad Digital Repository: https://doi.org/10.5061/dryad.n5tb2rbw2 (SI.1) and from https://beehave-model.net/download/. Supplemental Information via the Dryad Digital Repository includes an example BEE-STEWARD simulation video (SI.2), quick start guide (SI.3), detailed manual (SI.4) and an example automatic report (SI.5) (also provided as Supporting Information). A guide to creating maps (SI.6), copyright and licence information (SI.7) detailed documentation of the changes to the code, scheduling, example exercises, comparison of BEE-STEWARD and Bumble-BEEHAVE simulation results, and an overview of simulated processing are provided via the Dryad Digital Repository (SI.8). Descriptions of the underlying models, scheduling, parameterisation, sensitivity analysis and manuals are in the Supplementary Materials of the BEESCOUT and Bumble-BEEHAVE publications.

3 | COMPARING BEE-STEWARD WITH BEESCOUT (2.0) AND Bumble-BEEHAVE

By integrating the BEESCOUT and Bumble-BEEHAVE agent-based models, the new BEE-STEWARD software tool is easier to use whilst capable of producing the same results (SI.8) and having increased features (Table 1).

User-friendly features:
- The number of interface inputs, buttons and monitors etc., reduced to those associated with land management.
- A step-by-step approach guides the user through the control panel and the user messages.

**FIGURE 2** Model structure and relationship between user actions, input files and model processes of the BEE-STEWARD software tool. Model processes ANALYSIS, SETUP and GO, enable users to create and set up a map, run it with the bumblebee behaviour, colony growth and population model, and gain results using one tool.
• One interface to input, create and modify resource maps, run the bumblebee behaviour, colony growth and population model, and compare results between two maps representing land management scenarios.

Additional functionality:

• Unlimited habitat or crop types. The restriction of nine habitat types in BEESCOUT (2.0) has been removed. Habitats can be defined by any of the NetLogo ‘color swatches’ as a decimal number between 0 and 139.9 via the ‘HabitatsFile’.

• Unlimited bumblebee species. New bumblebee species can be defined via the ‘BeespeciesFile’ without modifying the code.

• Adding ‘Stewardship’ options. Crop fields can be selected and modified by adding relevant Agri-environment scheme management options by selecting either a flower-rich plot, margin or legume-rich crop option (e.g. AB1, AB8 and AB15 respectively in the current Countryside Stewardship scheme, DEFRA, 2020), and applying it to that field. Default flowering resources for each Stewardship option can be used (number of flowers per m² from Ouvrard et al., 2018), or users can edit the ‘HabitatsFile’.

• Enabling crop rotations. Users can annually change resources by rotating through a user-defined sequence of maps. This could reflect crop rotation on agricultural fields or changes in semi-natural habitats over time to reflect habitat restoration.

• Creating an automatic report. A simple option has been added to quickly compare two landscapes representing different management options and the relative number of bumblebee colonies and individual adult bees they support. This option can be selected from the interface and is for users not familiar with the analysis of computer models.

4 | EXAMPLE SIMULATION: TESTING MANAGEMENT SCENARIOS ON FARMLAND

4.1 | Example setup

We provide a simple example of how BEE-STEWARD could be applied using a map of a realistic farmed area with and without intervention options to predict its suitability to support bumblebee populations. The default BEE-STEWARD model settings were used (unless stated otherwise) starting on 1st January with 8 hr of foraging time per day.
Table 1. Maximum number and date of bumblebee colonies and pollinators in year 5 and the change in maximum numbers of colonies and pollinators from year 1 to 5 as a percentage (trend).

| My Map            | Colonies       | Pollinators   |
|-------------------|----------------|---------------|
|                   | max | date   | trend (%) | max | day   | trend (%) |
| Example_Farm_Baseline | 7   | 07-Apr | -30       | 100 | 03-Jun | -31       |
| Example_Farm_plot  | 33   | 04-May | 194       | 377 | 26-May | 96        |

Figure 1. Colonies (a) and pollinators (b) (mean) over final 3 years (error bars = Standard Error).

Figure 2. Number of bumblebee colonies over 5 years.

Figure 3. Number of bumblebee pollinators over 5 years.

Figure 3  The automatic report (PDF) generated by the BEE-STEWARD tool comparing the max and mean relative number of bumblebee colonies and adult workers (pollinators) over 5 years (n = 20) from two simulations representing different management scenarios of a baseline (Example_Farm_Baseline) and adding a 0.5 ha flower-rich plot (Example_Farm_plot).
As the example map was small (1.5 km by 1 km), the initial number of Bombus terrestris queens was set to 100.

The example represented a relatively resource-poor landscape, consisting of semi-improved pasture and maize with little hedgerow, scrub and permanent pasture. Intervention options were implemented using the Stewardship Options panel on the control panel of the BEE-STEWARD interface to transform 0.5 ha of a maize crop field (3.07 ha in size) into a flower-rich 'plot'. Default species and the number of flowers are the same for each Stewardship options. The precise number of flowers for these options in the field will depend on seed mix, soil type, slope, management and region etc., so users are encouraged to edit these values in the 'HabitatsFile' to their circumstances for more accurate predictions.

Simulations of the farmland with and without intervention options were run using the BEE-STEWARD Automatic report function for a 'Full simulation'. This runs for 5 years, for 20 random seeds (N = 20), and records the relative number of bumblebee colonies (referred to as 'colonies') and adult worker bumblebees (referred to as 'pollinators') in each simulation. Results are saved in a csv file and provide relative estimates that can be used to compare the outcome of different land management scenarios. However, due to the complexity of the system, results should be interpreted cautiously and not used to predict the absolute number of colonies found in a real landscape.

4.2 | Example results

Results (Figure 3) showed that a 0.5 ha pollinator-friendly intervention plot resulted in a higher maximum number of colonies than the example baseline map (7 and 33 respectively) and a higher number of pollinators (i.e. the number of bumblebee adult workers from the colonies foraging on the map, 100 and 377 respectively) in year 5. There was a higher mean number of colonies (2.19 and 7.25 respectively) and pollinators (22.17 and 80.16 respectively) over the last 3 years of the 5-year prediction for the pollinator-friendly intervention plot scenario compared to the baseline. Over the 5 year simulation, there was an increase in the number of colonies and pollinators (194% and 96% respectively) for the pollinator-friendly intervention plot scenario and a decline in the number of colonies and pollinators for the baseline scenario (30% and 31% respectively).

5 | CONCLUSIONS

BEE-STEWARD is a decision-support tool for researchers, policymakers and practitioners to predict the impact of land-use change on bumblebee colony and population dynamics. The user-friendly interface and additional functionality have been co-developed with and for researchers, land advisors and land managers through stakeholder consultation to increase the likelihood of uptake (Rose et al., 2016; Rossi et al., 2014). As a result, BEE-STEWARD is already being used by researchers and conservation organisations, which are adapting the default input options to reflect bespoke land management scenarios (Bumblebee Conservation Trust, 2020; Knapp et al., 2019; Roberts, 2019).

BEE-STEWARD is also an important virtual test bed for scientists exploring the impacts of multiple different stressors on bumblebees, who benefit from the improved user-friendliness and expanded functionality of the underlying models. These users can create input maps via Geographical Information System (GIS) programs and systematic model analyses with NetLogo's 'BehaviorSpace'.

BEE-STEWARD enables users with little or no experience of the BEEHAVE family of models to:

1. Build bespoke scenarios of different real-life management options by importing, creating and modifying mapping data.
2. Realistically reflect the floral resources, landscapes and bumblebee species of a given landscape by editing default input files to represent an infinite number of bumblebee and flower species and unique habitats and crops.
3. Explore landscape-scale questions about bumblebee population survival relating to the spatial and temporal dynamics of floral resources.
4. Transition away from a one-size-fits-all approach to one better designed at optimising future land management use such as new Agri-environment schemes.
5. Compare predictions of the relative bumblebee colony densities between landscape management scenarios to aid robust decision-making for land management to support bumblebee populations.

The BEE-STEWARD tool illustrates how complex systems models can be re-engineered and expanded through stakeholder consultation into an open-source, user-friendly, decision-support tool enabling a shared methodology between research, policy and practice in support of bumblebee survival.

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AUTHORS’ CONTRIBUTIONS
G.T.-D. wrote the manuscript, contributed to model development, lead stakeholder consultation and ran model simulations; M.A.B. was the model developer, wrote the model documentation, and co-wrote the manuscript; J.L.O. co-designed the projects, contributed to model development and co-wrote the manuscript. All authors gave final approval for publication.

PEER REVIEW
The peer review history for this article is available at https://publo ns.com/publon/10.1111/2041-210X.13673.
DATA AVAILABILITY STATEMENT

The BEE-STEWARD tool and all associated data and documentation needed to run the tool will be available for download via the Dryad Digital Repository https://doi.org/10.5061/dryad.m5tb2rw2 and on the https://beehave-model.net/download/ website on publication.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

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