



ERA modelling tool for wild and honey bees ready for EFSA

Deliverable D8.4

31 May 2023

Jordan Chetcuti¹, Elżbieta Ziółkowska², Xiaodong Duan¹, Trine Poulsen¹, Astrid Holm Andersen¹, Luna Kondrup Marcussen¹, Christopher John Topping¹

¹Aarhus University, ²Jagiellonian University, Kraków

PoshBee

**Pan-european assessment, monitoring, and mitigation
of stressors on the health of bees**



Prepared under contract from the European Commission

Grant agreement No. 773921

EU Horizon 2020 Research and Innovation action

Project acronym: **PoshBee**
 Project full title: **Pan-european assessment, monitoring, and mitigation of stressors on the health of bees**
 Start of the project: June 2018
 Duration: 60 months
 Project coordinator: Professor Mark Brown
 Royal Holloway, University of London
www.poshbee.eu

Deliverable title: ERA modelling tool for wild and honey bees ready for EFSA
 Deliverable n°: D8.4
 Nature of the deliverable: Other
 Dissemination level: Public

WP responsible: WP8
 Lead beneficiary: AU: Aarhus University

Citation: CHETCUTI, J., ZIÓŁKOWSKA, E., DUAN, X., POULSEN, T., HOLM ANDERSEN, A., KONDRUP MARCUSSEN, L. & TOPPING, C.J. (2023). *ERA modelling tool for wild and honey bees*. Deliverable D8.4 EU Horizon 2020 PoshBee Project, Grant agreement No. 773921.

Due date of deliverable: Month 60
 Actual submission date: Month 60

Deliverable status:

Version	Status	Date	Author(s)
1.0	Draft	15 May 2023	CHETCUTI, J., ZIÓŁKOWSKA, E., DUAN, X., POULSEN, T., HOLM ANDERSEN, A., KONDRUP MARCUSSEN, L. & TOPPING, C.J. (2023). Aarhus University

The content of this deliverable does not necessarily reflect the official opinions of the European Commission or other institutions of the European Union.

Table of contents

Preface	4
Summary	5
1. Introduction	6
2. Landscapes	7
2.1. Landscape Generation Overview	7
2.1.1. Landscape representation in ALMaSS	7
2.1.2. Major categories of data needed for the generation of the ALMaSS landscape model	7
2.1.3. Overview of the processing steps	9
2.2. Landscape Selection and Data Generation	12
2.3. Floral resource models	21
2.3.1. Models of flowering phenology	22
2.3.2. Pollen, nectar and sugar production levels	23
2.3.3. Composition of 'bee-friendly' plants in the main landscape elements/habitat units and flowering density	23
2.3.4. Implementation of floral resource models in ALMaSS	24
2.4. Pesticide model	25
3. Bee models	26
3.1. Overview of the <i>Bombus terrestris</i> model	26
3.2. Overview of the <i>Osmia bicornis</i> model	28
3.3. Overview of the <i>Apis mellifera</i> (ApisRAM) model	30
3.4. Overview of the pesticide toxicity model	32
4. ERA modelling tool interface	32
5. Example Scenarios	34
5.1. Pesticide impact	34
5.1.1. Scenario description	34
5.1.2. Indicative results	35
5.2. Mitigation measure	37
6. Description of the content of the digital delivery	39
6.1. Instructions for setting up and starting Docker and Shiny.	39
6.1.1. Installing docker and ALMaSS PoshBee image:	39
6.1.2. Running ALMaSS PoshBee docker image	39
7. Conclusion	40
8. Acknowledgements	40
9. References	41

Preface

This deliverable D8.4 provides an easy-to-use interface for the ERA modelling tool for wild and managed bees. Agent-based models have been developed for three bee species, the buff-tailed bumble bee (*Bombus terrestris*), a solitary bee, the red mason bee (*Osmia bicornis*), and the honey bee (*Apis mellifera*) (Figure 1). The development of these three models, *B. terrestris*, *O. bicornis* and *A. mellifera* were conducted as part of PoshBee, a Polish National Centre funded project and direct European Food Safety Authority (EFSA) funding respectively. Each species model was parameterized with detailed data on the species' biology and ecology. Coupled with detailed spatio-temporal landscape models, the species models simulate the life of each individual bee from egg to adult in realistic environmental conditions. This comprises a tool for evaluating the effects of different landscape management strategies on bee populations. The interface provided with this deliverable 8.4, allows EFSA users to run each of the three bee models in a selection of landscapes from several European countries representing different pedo-climatic zones across Europe and under different scenarios of pesticide usage with or without flower strips for the purpose of future environmental risk assessment (ERA). This tool is particularly important given the potential impact of pesticides on bee populations and the urgent need to develop effective strategies for mitigating this impact.



Figure 1. A buff-tailed bumble bee (*Bombus terrestris*) gyne and a honey bee (*Apis mellifera*) foraging in early spring in Denmark; one of the countries in which the model can be run.

Summary

Our ERA tool is the result of years of model development within the Animal, Landscape and Man Simulation System (ALMaSS) framework (Topping et al., 2003), including three bee models, and the modelling of landscape, pollen and nectar, and pesticide applications. The user interface of our tool enables the running of scenarios for the three bee species on different landscapes in several European countries representing different pedo-climatic zones across Europe, with and without pesticides and/or flower strips. In this summary, we provide an overview of the underlying components of the interface and explain how to access and run it.

The ALMaSS models use detailed spatiotemporal representations of landscapes with one-metre spatial resolution, an hourly temporal resolution of weather, and a daily temporal resolution of landscape management. The spatial map represents actual land use/land cover and is linked with a dynamic component simulating the growth and biomass of plants, nectar and pollen production, and farm management on each agricultural field. We have made available ten landscapes which we selected to have at least 50-60% arable land in each of the selected counties co-developed by several National and EU projects. These include Poland, Germany, Denmark, Netherlands, Belgium, and Finland, with France imminent.

To enable bees to forage within the landscape, we developed floral resource models that realistically simulate nectar and pollen production per unit area of natural habitats and managed crops within a landscape. These resources directly drive the growth of individual bees, their offspring, and in the cases of *Bombus terrestris* and *Apis mellifera*, their colony or hive. The floral resource models also allow for the simulation of the exposure of bees to pesticides. The pesticide is modelled in six compartments, the plant surface, soil, in-plant, pollen, nectar, and seed coating through three types of application. Bees are exposed to pesticides either through ingestion of pollen and nectar, contact with pesticides on the surface of plants, or direct over-spraying. The pesticide degrades within the bees but causes damage, which increases their chance of dying. Sublethal effects are included in the ApisRAM model, and while not included in the *B. terrestris* and *O. bicornis* models at present, they will be added in future versions.

Our tool features three bee models: *Bombus terrestris*, *Osmia bicornis*, and *Apis mellifera* (ApisRAM). The *B. terrestris* model starts with hibernating gynes that awake in spring, forage, and found nests. As a queen, she warms her nest, lays eggs, and cares for the young. Once the first workers emerge, they take over much of the brood care and foraging for the colony. As the colony grows larger, gynes and males emerge and leave the colony as it diminishes and then dies. The gynes and males mate and then the gynes forage, search for a hibernation site and then hibernate. *Osmia bicornis* is a solitary bee that overwinters within the nest as an adult in cocoon. Adults emerge in spring, forage, and establish nests in pre-existing cavities. Each brood cell in a nest is then provisioned with a mixture of pollen and nectar, and an egg is laid on top of the provisions. The adult females then die, and the eggs develop into larva which feed on the provisions and pupate. All immature life stages develop in sealed brood cells within the nest, and only adult bees interact with the external environment. The ApisRAM model starts as an established hive with only adults, a queen and stored resources. In spring, bees start to forage, and the queen starts laying eggs. The bees forage for resources in all three cases, although with different focuses.

The ERA tool is an R Shiny app that enables the setting of parameters within the scope of the three bee models, running ALMaSS simulations, and comparing basic results. The user chooses the species and duration of the simulation and can set up one or two scenarios with different landscapes, with or without flower strips, and pesticides. Once complete, the model runs for each scenario, and the results are saved. The interface provides a graph of the number of bees in each life stage through time, which can be compared to past runs or outputs. Instructions for how to install and set up the interface can be found in section 6.1 “Instructions for setting up and starting Docker and Shiny.”

1. Introduction

Pollinators, such as wild and managed bees, play a crucial role in the pollination of crops and wild plants, contributing to food security and ecosystem functioning. However, the use of pesticides in agriculture, while often necessary for food security, poses a significant threat to pollinator health and survival, and therefore, to the ecosystem services they provide that benefit agriculture (Buczkowska and Kowalska, 2000). To aid in landscape-scale modelling of pesticide risks to wild and managed bees, we developed species models for two wild bee species, the buff-tailed bumble bee (*Bombus terrestris*), and a solitary bee, the red mason bee (*Osmia bicornis*), and another model for the managed honey bee (*Apis mellifera*). These three species were selected to be representative of bee diversity, as there is a great deal of difference between their social organization and behaviour, which makes them an appropriate representation of bee diversity for the purpose of environmental risk assessment. For instance, while honey bees have large, structured, and tightly managed hives, bumble bees spend part of the year as solitary individuals before establishing nests, whereas the red mason bee is a solitary species where individuals work alone throughout the lifecycle to provision a small number of eggs as the basis for the next generation.

The models were developed as agent-based (individual-based) models. Agent-based modelling is a method where a system is built from the bottom up using fine scale knowledge about the systems constituent units. In the case of animals this includes knowledge about the biology and ecology of individuals of each species including detailed information about energy budgets, behaviour and reproduction (Railsback and Grimm, 2017). This allows for the simulation of complex systems with multiple interactions and internal feedbacks and the prediction of emergent patterns under different scenarios, which is particularly useful for environmental risk assessment.

The models were developed under the framework of the Animal, Landscapes and Man Simulation System (ALMaSS), a modelling tool that simulates impacts of pesticides and landscape management on a variety of species in the agricultural landscape. ALMaSS landscape models simulate dynamic farm management and vegetation growth including floral resource modelling and a complex pesticide fate model. This allows for realistic simulations of bees in the landscape and how they are affected by the availability of floral resources and pesticide exposure.

The floral resource models combine ALMaSS landscape models with information on flower species phenology and flowering density within each habitat (mixed woodland, for example) to realistically predict daily production levels of nectar and pollen, which in turn drive the individual bee's biology. The amount of available food is determined by the configuration of the landscape and what flowering species are present. The floral resource models are driven by temperature.

Foraging within the landscape, bees can also be exposed to pesticides that have accumulated in their food, or through direct contact with pesticides either carried on the wind or sitting on the surface of the vegetation. The pesticides may appear on plant surfaces, in pollen and nectar, and on soil. This happens through direct spraying as well as drift caused by wind. Within the model, pesticides are also introduced into the system through seed coatings and granular applications. Once in the environment they are then transferred between compartments, i.e., within-plant, plant surface, soil, seed, and nectar and pollen. The pesticides also degrade within these compartments over time. The foraging bees collect nectar and pollen when foraging and can be exposed to pesticides through direct contact with the pesticides on the plant surface and spraying, and through the nectar and pollen they consume.

To allow different scenarios to be explored it is possible to turn pesticide application within the simulation on and off and define different application rates and rates of decay for when it is on. We have created an interface in R shiny that allows a user to choose between the three bee species to be simulated, set the modelling environment as one of ten landscapes from one of the selected countries,

and decide whether to use a measure aimed at supporting pollinators, that is, adding flower strips. Within the interface the user can choose to run up to two scenarios simultaneously and to save the outputs. As this may take some time, the user can then compare these two scenarios or any of the previous scenarios they have saved. The user can look at the different effects of the scenarios on each of the life stages of the bee species, but also perform additional analysis outside the tool on the saved output files. This interface has been packaged in such a way that a user can use the interface without a complex understanding of the model framework and will benefit from updates and improvements both to ALMaSS and the interface.

The following sections describe the generation of ALMaSS landscapes, each of the three species models, pesticide application implementation and how to interact with the ERA interface.

2. Landscapes

2.1. Landscape Generation Overview

2.1.1. Landscape representation in ALMaSS

The simulation system used, ALMaSS, is an open-source project hosted on GitLab (<https://gitlab.com/ALMaSS/>) (Topping et al., 2010). ALMaSS integrates agent-based models of selected species with detailed descriptions of an environment (landscape) from which modelled individuals obtain information necessary to simulate their behaviour.

In ALMaSS, landscapes are modelled using a detailed, spatio-temporal representation which provides a realistic environment for agent-based simulations of the focal species. In this representation:

- Spatial landscape heterogeneity is described by a detailed raster land cover map with complete coverage and spatial resolution of one metre. Each unit in the raster land cover map is classified in accordance with its landscape element type (e.g., natural or permanent grassland, field in rotation, built-up area), including detailed structures important for the species under consideration, such as hedgerows or field margins. To account for crop diversity, field boundaries are also added, with each field belonging to a given farm unit (managed by the same farmer). Farm units are classified into different types, e.g., cattle, pig or arable farms, based on structure of crops grown and animals present in the farm. This structure allows the incorporation of information on farm management to the description of spatial heterogeneity at a given point of time (Topping et al., 2003, Topping et al., 2016).
- Temporal landscape heterogeneity includes both crop management throughout a year, described through individually tailored management plans for each crop, and the cropping system understood as a multi-year crop rotation. Associated vegetation growth models for all modelled vegetation types and crops supply vegetation height, green and total daily biomass, and are fed by weather conditions (mean daily temperature, mean daily wind speed and daily sum of precipitation).

The generation of the ALMaSS landscape models follows the methodology described in detail in Topping et al. (2016), and it is based on previous experiences with model landscape generation for Denmark. The whole process can be divided into the following sub-tasks: (i) spatial (landscape) and non-spatial data collection & quality check, (ii) ALMaSS landscape map generation (spatial component), (iii) incorporation of crop management & vegetation growth (dynamic component).

2.1.2. Major categories of data needed for the generation of the ALMaSS landscape model.

The generation of the ALMaSS landscape model is based on information from different data sources of sufficiently high resolution and quality (Figure 2).

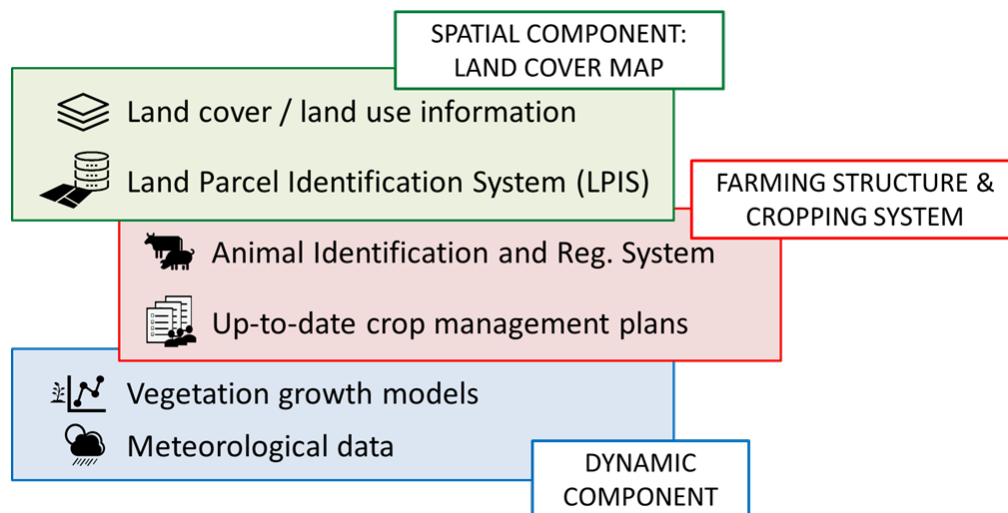


Figure 2. Main types of input data needed for generation of the ALMaSS landscape model.

The following categories of data are necessary:

- i. Land use/land cover information including the map layers presenting natural and/or semi-natural landscape elements (e.g., rivers or streams, lakes, bare sand or rock, steep slopes); natural or semi-natural vegetation (e.g., hedgerows, open vegetation types, forest, isolated trees); infrastructure (e.g., roads, buildings or industry); and protected areas.
- ii. Such information usually comes from different data sources, but in most cases the topographic object databases with level of details corresponding with topographic maps at the scale of 1:5000 – 1:25000 are the most important source of land cover/land use information needed for the ALMaSS landscape model generation.
- iii. Agriculture (e.g., field boundaries linked to farm management) - Under the Common Agricultural Policy (CAP), if farmers want to apply for the EU subsidies, they are obligated to report for each individual reference parcel the crop/crops they grow (with information of area of each crop grown) and the number of livestock they own. The Land-Parcel Identification System (LPIS) has been developed in each of the EU countries to support CAP and it stores geographic information on 'reference parcels'. Different types of 'reference parcels' can be used including (i) agricultural parcels, (ii) farmer blocks, (iii) physical blocks, and (iv) cadastral parcels, depending on the country. The data on 'reference parcels' together with agricultural register (related information on type of crops grown and their coverage) needs to be merged with the land use/land cover information from (i).
 Since the parcel layer is based on subsidy payments from the EU, and it is mandatory for farmers claiming subsidy to make the delineation/definition of the parcel(s), this layer has various level of detail depending on the country/region. On those landscape windows where the information regarding the field parcels is too scarce or incomplete, one strategy is to use fine spatial resolution image data (e.g., Sentinel-2 time series data, orthophoto) and pixel and object-based image processing and analysis methods to determine the field boundaries and the crop types.
- iv. Farm animal data (Animal Identification and Reg. System) - together with the register of crops these data are used to classify farm units into general farm types.
- v. Soil type information for vegetated landscape elements – as the ALMaSS landscape simulator modifies the actual production on each field based on the dominant soil type. Soil data at the EU level were obtained from the European Soil Database provided by the Joint Research Centre.

- vi. Weather data – including historical data on mean daily temperatures, wind speed and daily sum of precipitation for at least 10 years. At the EU level these data can be obtained from the European Climate Assessment & Dataset project.
- vii. Up-to-date crop management plans – describing time windows and probabilities of occurrence of all farming operations including soil cultivation practices, as well as fertilizer and pesticide applications.
- viii. Vegetation growth models if not already in ALMaSS. Inside the model landscape, all vegetation types and crops have their own seasonal growth models supplying vegetation height, green and total, biomass.

2.1.3. Overview of the processing steps

Generation of the ALMaSS landscape map (spatial component)

Generation of the ALMaSS landscape map (spatial component) was done by combining individual layers of land use/land cover information together with information on agricultural fields into a single raster landscape map in a step-by-step process. As layers from different data sources were used, this resulted in inconsistencies related to spatial alignment of features (i.e., overlaps or gaps between features). In addition, some objects were represented as points or lines (dimensionalities of 0 and 1) and had first to be pre-processed in order to change them into two-dimensional ones. However, this process increased the number of inconsistencies in the combined map even more, so a special step-by-step procedure was applied to be able to obtain a landscape raster map with no gaps in information and with removal of sliver polygons.

The overall process to generate the ALMaSS landscape map consisted of the following general steps (although some specific processing steps were needed in the case of each country due to specific national/regional data):

- i. Clipping the input layers to the study area extent;
- ii. Converting the input vector data to raster format (with spatial resolution of 1 m), object class by object class;
- iii. Combining individual layers into thematic maps (e.g., transportation theme, built-up theme);
- iv. Stacking of thematic maps to generate a raw landscape map (Figure 3);
- v. Reclassification of large 'background' polygons, and removing of inconsistencies in the landscape raw map (multi-stage process);
- vi. Reclassification and regionalization of the resulting landscape map. The landscape map contains more details than are used in ALMaSS. Therefore, to be consistent with landscape element types used in ALMaSS we used simple reclassification based on a text file (separate for each analysed country). All features in the ALMaSS landscape map, consisting both of single and multiple raster cells, have a unique value that is common to all cells within the feature. This was achieved by regionalizing the raster before exporting the map as a final ASCII file.
- vii. Exporting results;
- viii. Generating input files for ALMaSS.

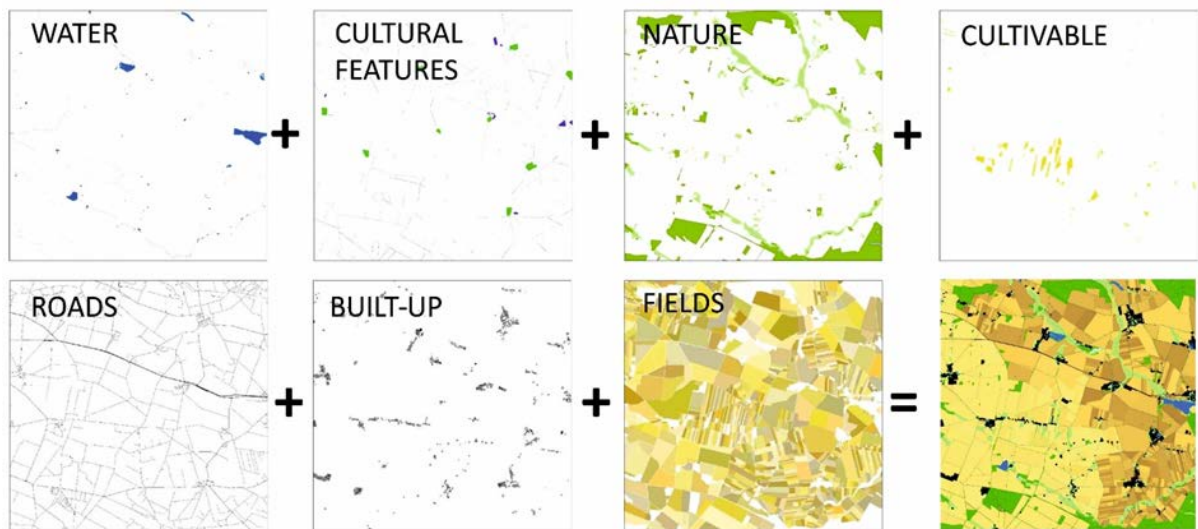


Figure 3. Stacking of GIS layers.

Farming structure and cropping system

In ALMaSS, crop management is applied at the farm level, therefore individual agricultural parcels (fields) need to be grouped into farm units of different types (e.g., conventional cattle, pig or arable farms). Farm classifications were generated for each country/region separately based on LPIS and farm animal data.

Based on proportions of crops cultivated by farms of different types, crop rotation schemes can be generated for each farm type individually. Only crops with more than 1% share of the area of a farm type are considered. In such a case it is assumed that the rotation could be represented by 100 crops (1 crop for each 1%). The order of crops follows typical agronomic practices and issues such as late harvest leading to impossible sowing conditions are controlled by the built-in ALMaSS farm code. The result is a pattern of changing crops on a field that matches the overall crop distribution pattern for that farm type precisely over 100 seasons. If a specific crop, e.g., maize for silage, occurs 13 times out of 100 in the rotation, it will on average occur on 13% of all fields covered by that rotation at any point in time. It is also possible to use pre-defined crop rotation schemes.

Incorporation of crop management & vegetation growth (dynamic component)

Inside the model landscape, all vegetation types and crops have their own seasonal growth models supplying vegetation height, green and total biomass. The result is a dynamic landscape with all vegetation growing in response to the weather. Crops and other vegetation also respond to management. Crops will grow from sowing and respond to management events such as harvest and cutting, which are programmed into the ALMaSS according to crop management plans provided by farmer advisors or other experts from each analysed country (Figure 4). Non-crop vegetation can also be managed, e.g., roadside verges are mown during summer in the model.

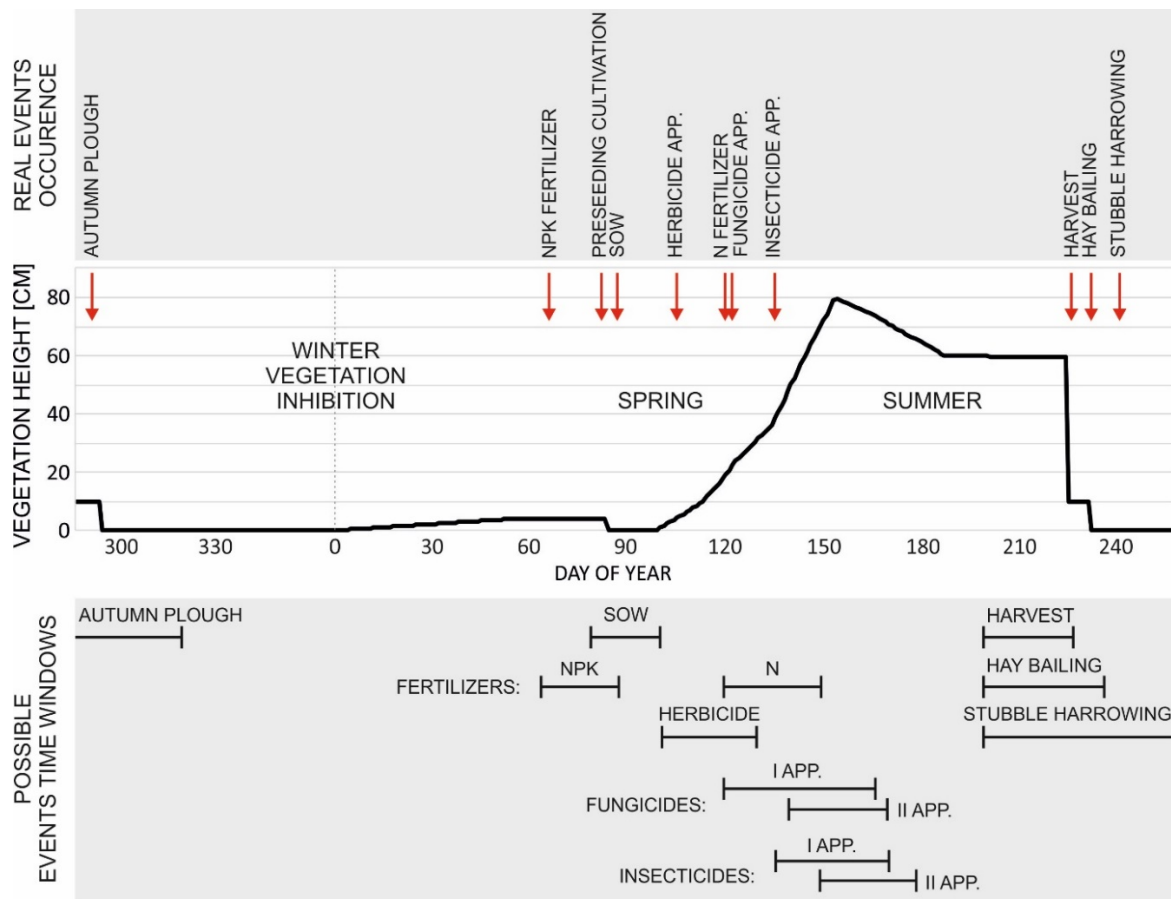


Figure 4. Crop management for spring barley on a field belonging to an arable farm in Poland.

Automatization

All handling and analysis of spatial data was done using Python 2.7 (Van Rossum and Drake, 1995)(<https://docs.python.org/2.7/>) and the Python library ArcPy to access ArcGIS features (Esri, 2020), or directly in ArcGIS 10.x (migration to open-source software is underway). The entire process of producing landscape models for ALMaSS has been programmed in Python scripts with Pandas library (McKinney and Others, 2010)(<https://pandas.pydata.org/>), separately for each country. As all procedures for generating landscape models for ALMaSS are automated or semi-automated, any landscape in each of the analysed countries/regions can be 'captured' and used for simulation (Figure 5).

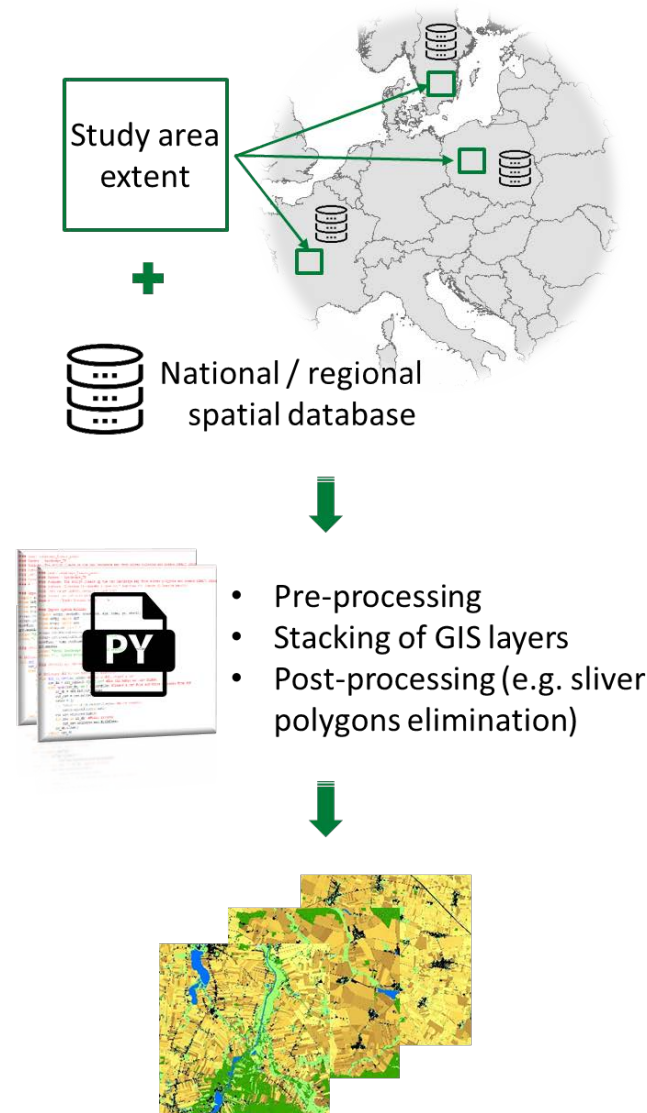


Figure 5. (Semi-) automated processing procedure.

2.2. Landscape Selection and Data Generation

Six countries were selected as representative for species modelling in both the EcoStack and PoshBee projects (due to the formal collaboration between these two projects). These are: Poland and Germany (Lower Saxony and Brandenburg regions) in the northern continental pedoclimatic zone, Denmark and the Netherlands in the Atlantic pedoclimatic zone, France (Auvergne-Rhône-Alpes region) in the southern continental pedoclimatic zone, and Finland in the boreal pedoclimatic zone. Since the ALMaSS landscape model for France is not yet fully operational (but will be in the near future), it has been replaced for the time being by Belgium (representing the Atlantic pedoclimatic zone) (Figure 6).

As we want to focus on agricultural landscapes dominated by arable land (i.e., where pesticide applications are a common threat for beneficial organisms), ten study areas of 10x10 km with at least 60% of arable land were further selected for modelling in each of these countries (Figure 7, Figure 8, Figure 9, Figure 10, Figure 11, and Figure 12) in such a way as to represent a gradient in the number of fields and average field size (see Figure 13). In Finland and Belgium it was not possible to find ten study areas of 10x10 km with at least 60% of arable land, so this threshold was lowered to 50%.

The ALMaSS landscape model for Belgium was developed within the B-GOOD project (the European Union's Horizon 2020 research and innovation programme, grant agreement No 817622). The ALMaSS landscape model for the Netherlands was developed within the project "Development and application of a methodology for assessing the interaction between pesticides and landscape structure" funded by the PBL Netherlands Environmental Assessment Agency. The ALMaSS landscape model for Germany was developed within the ELONTA project ("Evaluating the impact of landscape structure and source-sink dynamics on non-target arthropod pesticide risk assessments in Germany"), funded by the German Environmental Agency (UBA). Unfortunately, due to limited access to LPIS data on agricultural parcels, only two German regions could be modelled: Lower Saxony and Brandenburg. ALMaSS landscape models for Poland, Finland, and France have been developed within the EcoStack project. Access to LPIS data on agricultural parcels was also problematic in France, so that the ALMaSS landscape model could only be generated for the Auvergne-Rhône-Alpes region. The ALMaSS landscape model for Denmark already existed but was updated within the EcoStack project.

The protocols developed allow the automatic extraction of landscape data for landscape windows of a given size (typically 10 x 10 km) and the generation of the necessary ALMaSS input files for the simulation. Automatic extraction and compilation of data for simulation means that scaling can be applied by simulating multiple areas for a country using batch file processing on mainframe computers/clusters.

We are using a GitLab repository to store and distribute the open data products of this task (<https://gitlab.com/ALMaSS/almassauxillary> in a folder called 'landscape_generation'). These products include all the scripts that allow the (semi-)automated generation of the ALMaSS landscape models and other important input data.

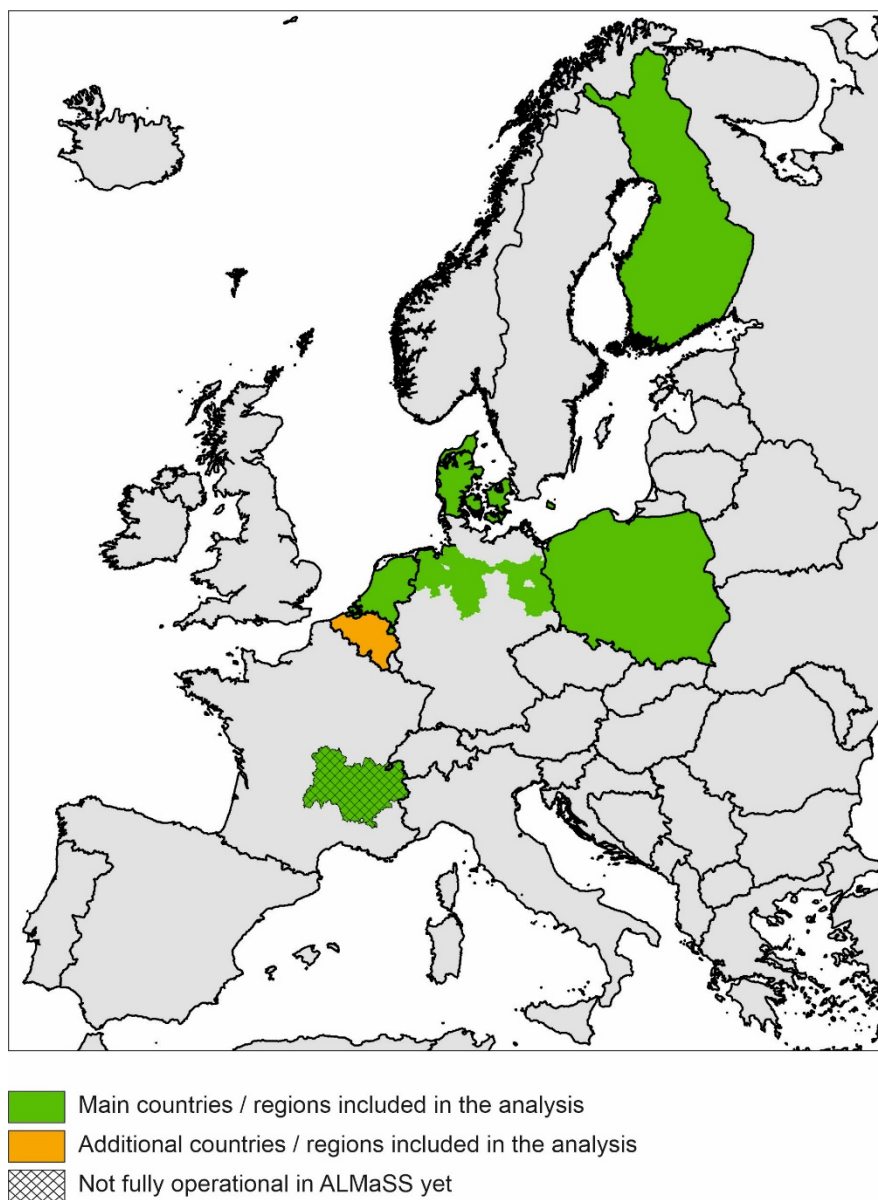


Figure 6. Current status of the ALMaSS landscape models used in the PoshBee project.

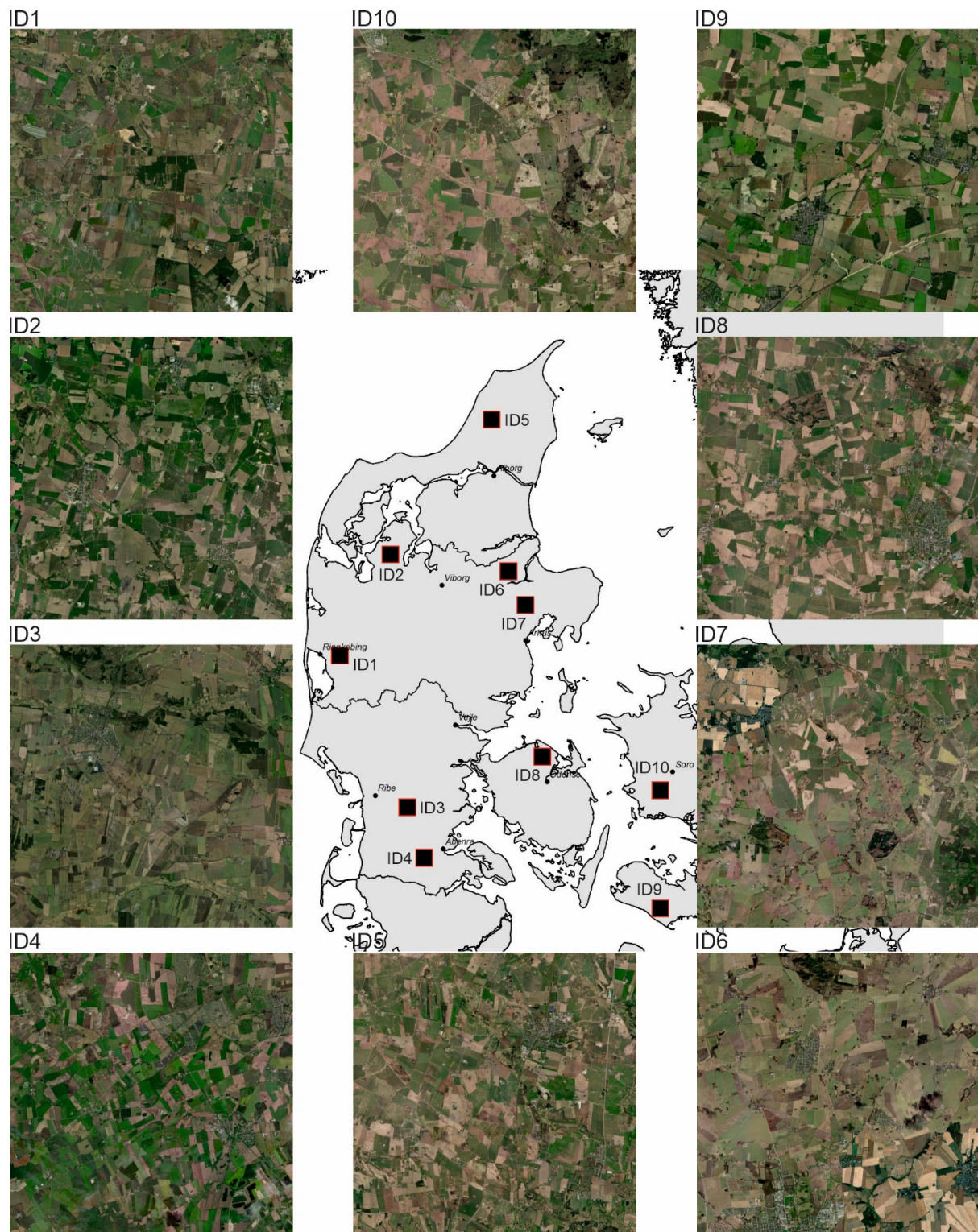


Figure 7. Map showing the 10 study areas and their locations for the set of Danish landscapes.

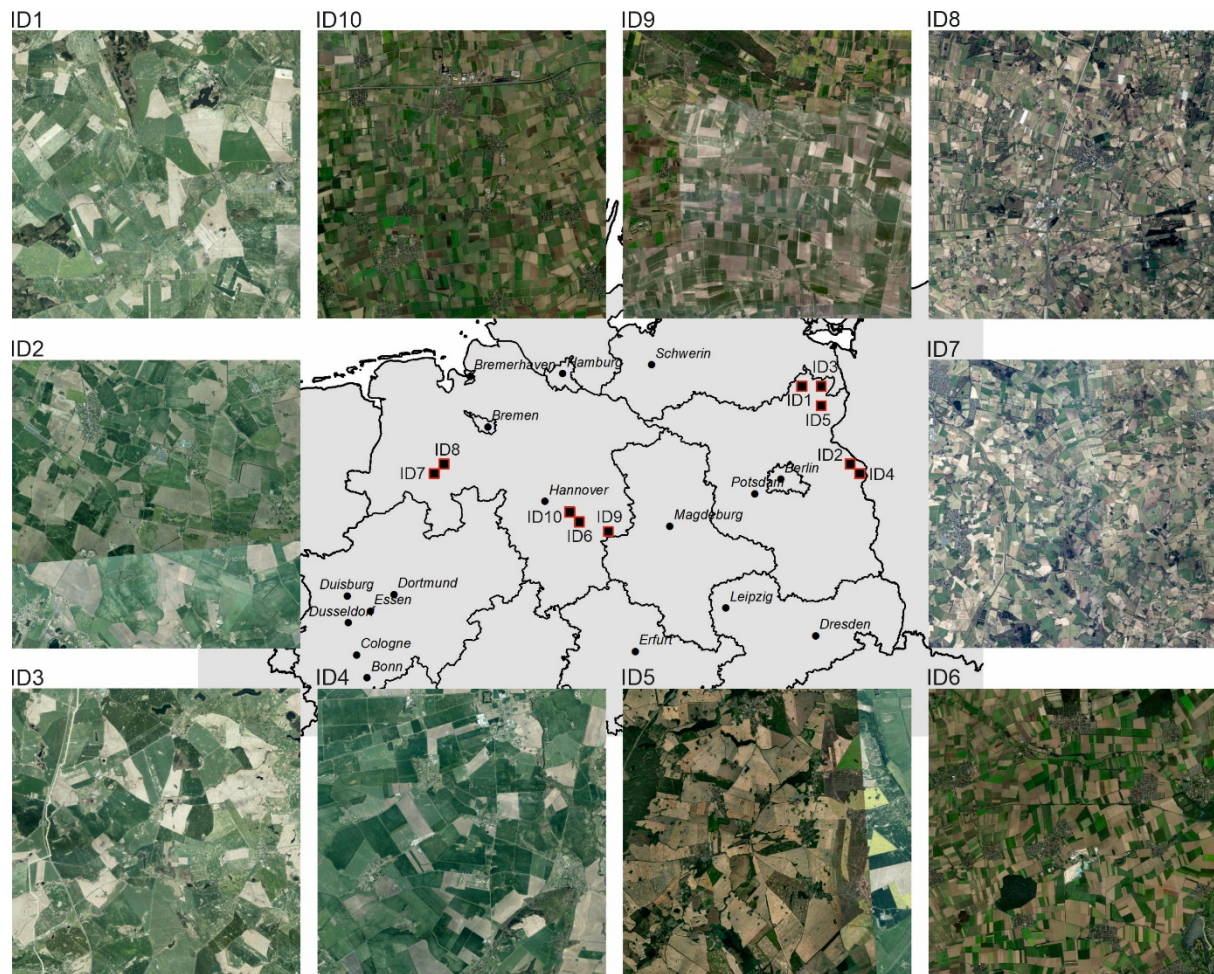


Figure 8. Map showing the 10 study areas and their locations for the set of German landscapes in two regions of Brandenburg and Lower Saxony.

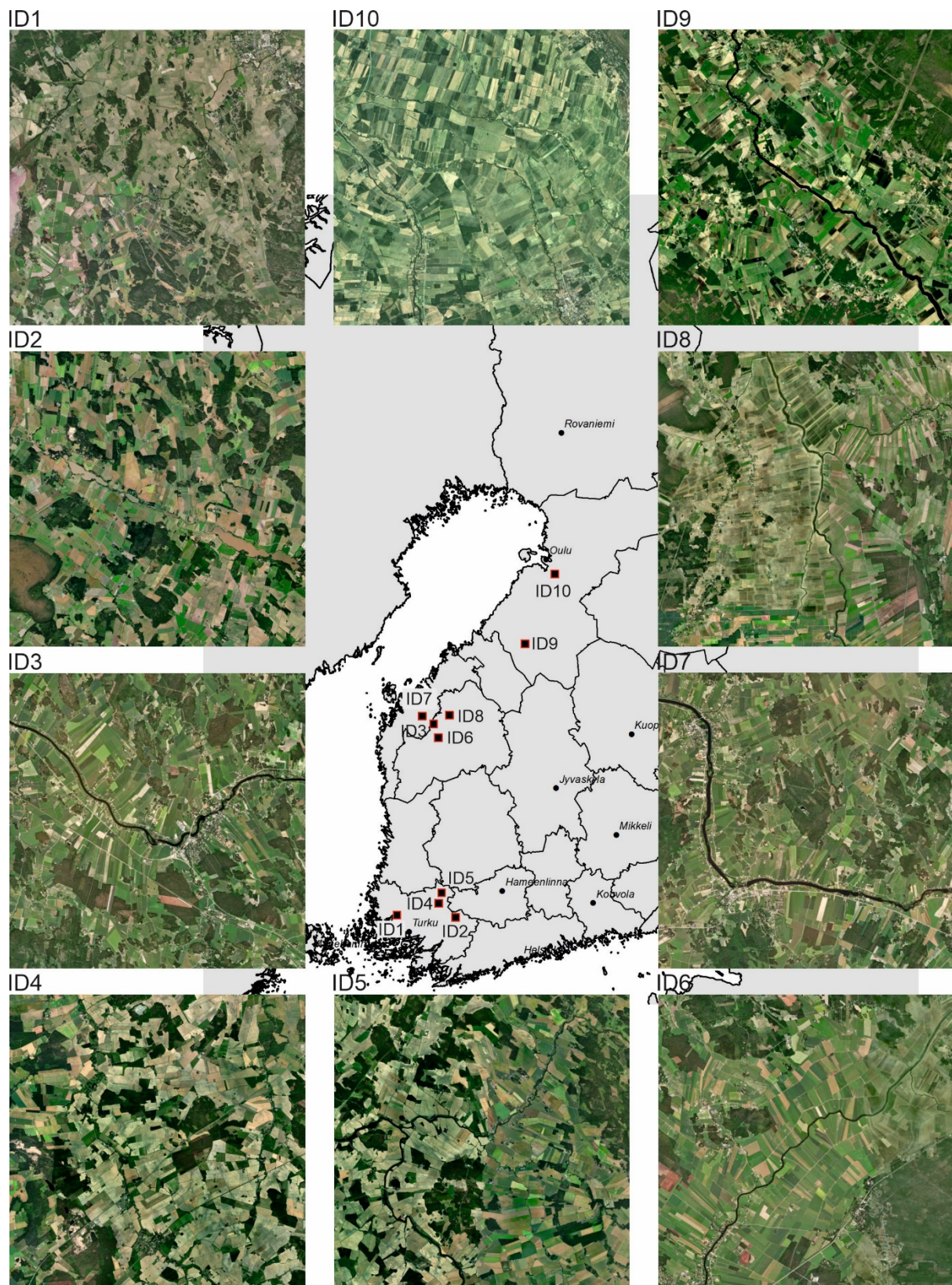


Figure 9. Map showing the 10 study areas and their locations for the set of Finnish landscapes.

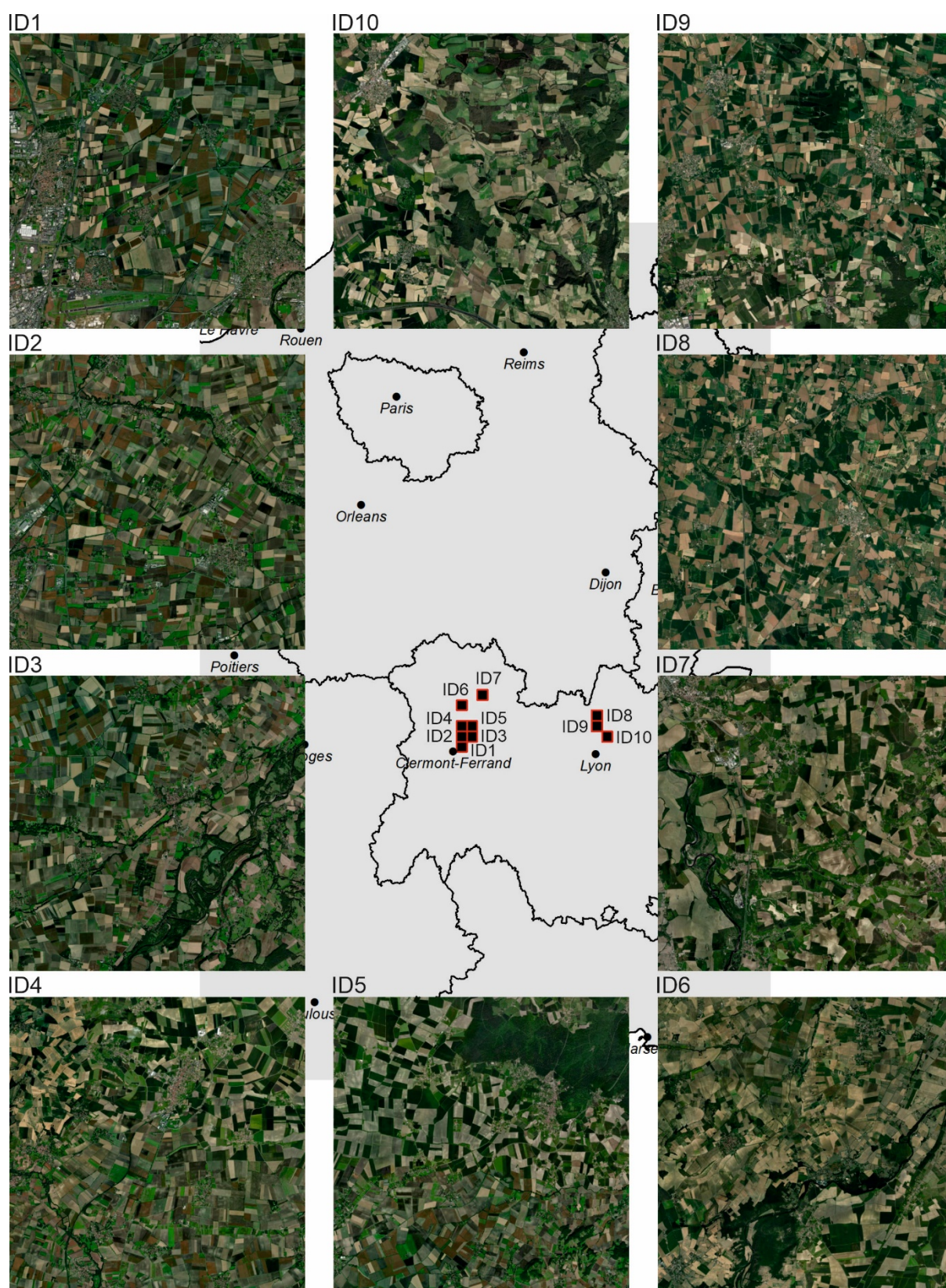


Figure 10. Map showing the 10 study areas and their locations for the set of French landscapes in the Auvergne-Rhône-Alpes region.

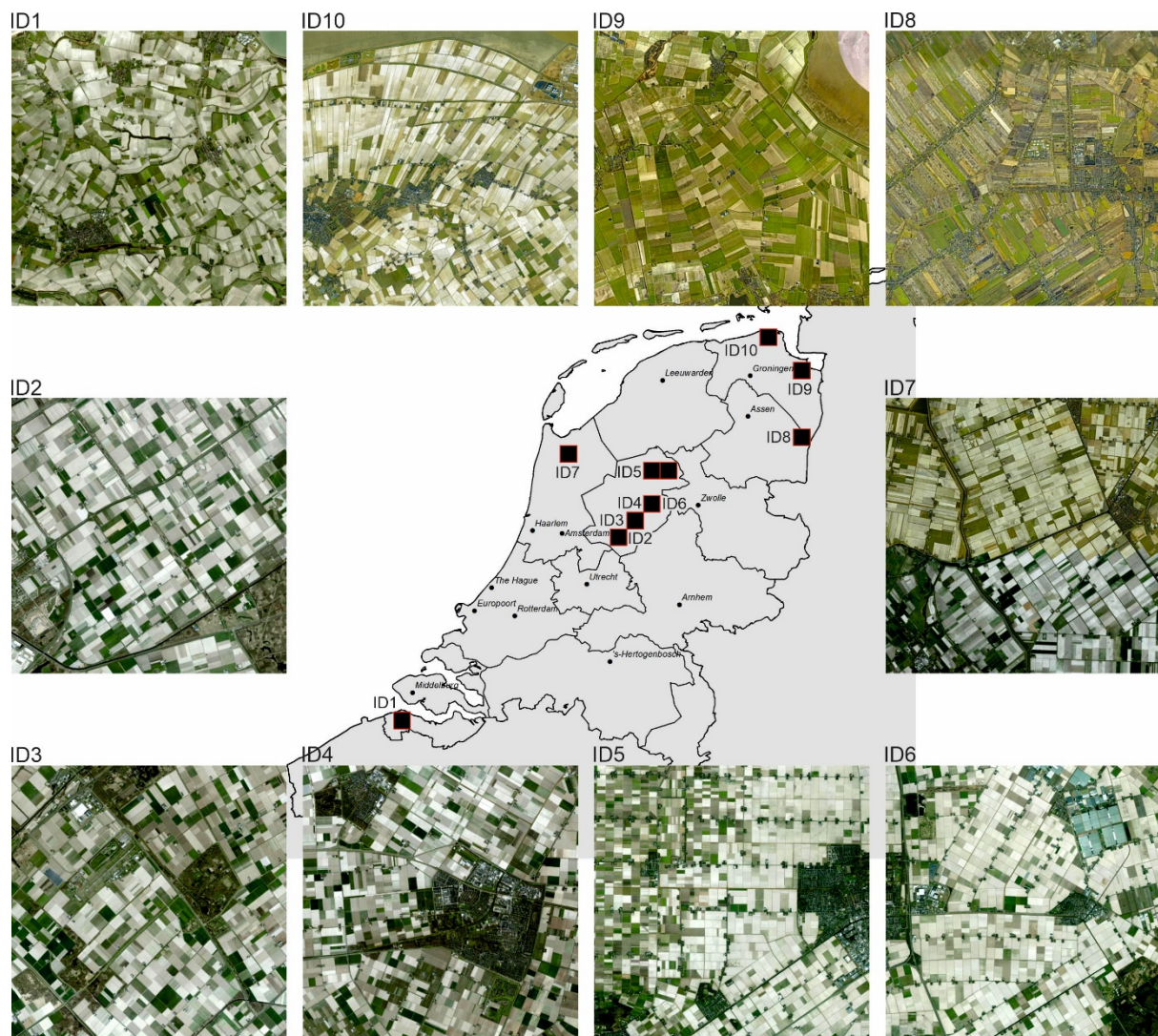


Figure 11. Map showing the 10 study areas and their locations for the set of Dutch landscapes.

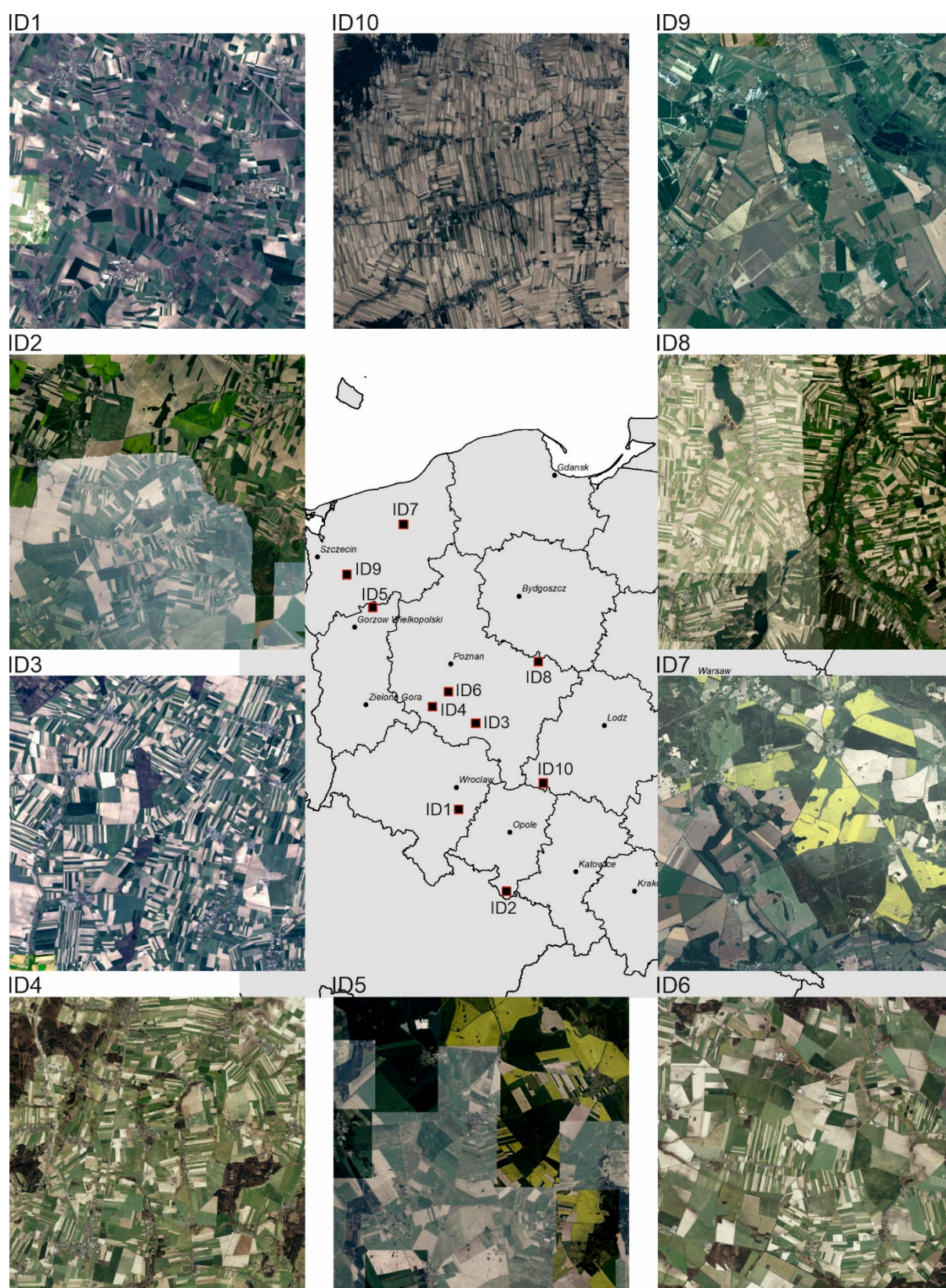


Figure 12. Map showing the 10 study areas and their locations for the set of Polish landscapes.

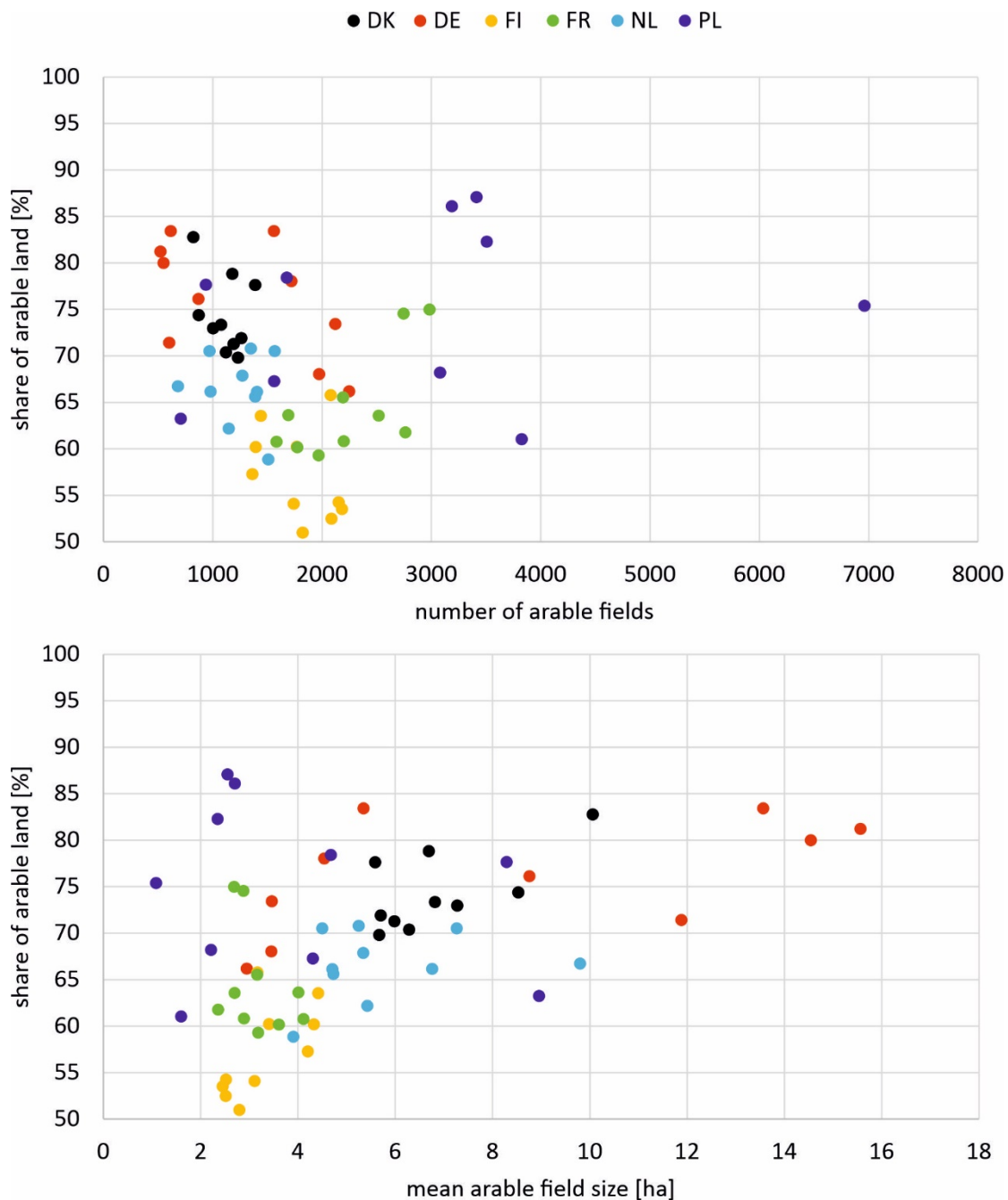


Figure 13. Basic characteristics of the study areas selected for simulations in the PoshBee project.

2.3. Floral resource models

Floral resource models describe pollen, nectar, and sugar production levels and their changes throughout the year. They are incorporated in the ALMaSS landscape model representation of landscape elements/habitat units and crops important to bees across Europe. The floral resource models are of crucial importance for pollinator models being developed under the ALMaSS framework. They have been developed within the European Union's Horizon 2020 research and innovation program (B-GOOD project; grant agreement no. 817622). Documentation and all the important input files for floral resource models are stored in an open GitLab repository (https://gitlab.com/ALMaSS/floral_resource_models). It is important to underline that these are

'living' documents, meaning that they are constantly being updated once new important datasets are published.

The floral resource models combine information on composition of 'bee-friendly' plants in the main landscape elements/habitat units important for bees across Europe with information on pollen, nectar, and sugar production per flower per day, and habitat-specific density of flowers per unit area. As the floral resource models need to be dynamic across the EU, the floral phenology of selected bee-friendly species is analysed in relation to growing degree-days. Therefore, integration of these data allows us to predict the amount of pollen, nectar and sugar produced by a given bee-friendly species per unit area of a specific landscape element/habitat unit as a function of accumulated growing degree-days. All the details on methodology behind generation of floral resource models are available in the deliverables of the B-GOOD project (D3.1-D3.4); below we provide a short overview.

2.3.1. Models of flowering phenology

In the current version of floral resource models, the timing of flowering is related only to temperature. This means that onset, peak and end of flowering are determined based on accumulated growing degree-days (GDD); i.e., degree days above the base temperature T_b , a temperature threshold below which plant development stops. For calculation of daily GDD the following formula is applied:

Daily GDD (°C) = Daily Average T °C – T_b °C, where

Daily Average T °C = (Daily Max T °C + Daily Min T °C)/2

If daily GDD is below 0 or daily average temperature exceeds the maximum temperature for growth T_{max} (i.e., a temperature above which plant growth is inhibited), the daily GDD is set to 0 meaning that there is no increase in accumulated GDD for that day.

For all wild plant species, GDD are accumulated starting from 1st January and using the base temperature T_b and maximum temperature for growth T_{max} obtained using optimization procedures aiming at selecting the best fitted flowering phenology models according to the root-mean-square error (RMSE). For crops we used crop-specific base temperatures, determined from the literature. For permanent crops (i.e., fruits, olives), GDD are accumulated starting from 1st January while for annual crops it is accumulated starting from the sowing date.

Models of flowering phenology were fitted based on data gathered in the database on floral phenology, currently including more than eight million observations. This database integrates the following data sources:

- Pan European Phenology Database (PEP725): <http://www.pep725.eu/> (Templ et al., 2018). The database records observations on phenological development stages of plants using the BBCH-scale. For our purposes only observations with BBCH of 60 (beginning of flowering), 65 (full flowering), and 69 (end of flowering) were selected.
- Phenological observations collected by the Deutscher Wetterdienst (German meteorological service, DWD) from 1951 to date accessed via Climate Data Centre OpenData server: https://opendata.dwd.de/climate_environment/CDC/. The observations of phenological development stages are described using specific codes of pheno-phases from 1 to 67 (description available at: https://opendata.dwd.de/climate_environment/CDC/help/PH_Beschreibung_Phase.txt), but in most cases the reference to the BBCH-scale is also provided. For our purposes only observations with codes of 5 (beginning of flowering), 6 (full/general flowering), and 7 (end of flowering) were selected.
- Phenological information from the database on nectar and pollen production (Filipiak et al., 2022) as a product of the B-GOOD project. This database represents the first compilation of

data on the various food resources produced by 1612 plant species belonging to 755 genera and 133 families, including crop plants and wild plants, annuals and perennials, animal- and wind-pollinated plants, and weeds and trees growing in different ecosystems under various environmental conditions. The data set consists of 103 parameters related to the traits of plant species and geographical and environmental factors, allowing for precise calculations of the amounts of nectar, pollen, and energy provided by plants and available to consumers in the considered flora or ecosystem on a daily basis throughout the year.

- Phenological observations of development stages of selected crops (including data on start and end of flowering of winter oilseed rape) collected by the Polish Official Variety Testing (COBORU) in years 2007-2016.
- Phenological observations from the multitaxon database on phenology from the Russian Federation, Ukraine, Uzbekistan, Belarus, and Kyrgyzstan (Ovaskainen et al., 2020). The data covers the period 1890–2018, with 96% of the data being from 1960 onwards. The database is rich in plants, birds, and climatic events, but also includes insects, amphibians, reptiles, and fungi. The database was restricted to plant flowering phenology observations within the spatial and temporal coverage of the E-OBS meteorological data.
- Flowering phenological observations collected by Jachuła et al. (2021) for bee-friendly species in human-made, non-cropped habitats of agricultural landscapes in SE Poland.

2.3.2. Pollen, nectar and sugar production levels

Pollen, nectar and sugar production from the flower/inflorescence of a given plant was assessed, in μg per day, based on the database on nectar and pollen production ((Filipiak et al., 2022); see details above). For each analysed plant species, we calculated the mean production of pollen, nectar and sugar from flower/inflorescence, in μg per day, from all available measurements (from different habitat types, years and locations). Often the number of total available measurements was very low, therefore merging measurements from different habitat types was necessary. In addition, the variance in floral resource production observed in between years and locations was often greater than between different habitat types. If less than two independent measurements of pollen, nectar and sugar production from flower/inflorescence in μg per day were available at the species level, the production of floral resources was estimated at the genus level, or if not possible – at the family level. In some situations, if other data were not available, production of floral resources (especially for pollen) was estimated from the yearly yield.

2.3.3. Composition of 'bee-friendly' plants in the main landscape elements/habitat units and flowering density

For the main landscape elements/habitat units (such as woodland and forests, grasslands, mires, bogs and fens, heathlands, shrubs and tundra), the 'Database of relevant resources for honey bees' produced within the B-GOOD project (as deliverable D3.1) was the main source of information. The database includes information on plant species occurrence and average plant species cover within the EUNIS terrestrial Level 2 habitats divided into biogeographical regions. The EUNIS (the European Nature Information System; <https://eunis.eea.europa.eu>) habitat classification is a pan-European hierarchical system that covers all types of habitats from natural to artificial areas, from terrestrial to freshwater and marine environments. The EUNIS habitat classification is a very detailed hierarchical system organized from Level 1 to Level 8, and across the different levels there are a total of 5284 different habitat types. Each habitat is identified with a specific and unique code, a name, and a description. In this case only the terrestrial EUNIS habitats at level 2 were used.

ALMaSS landscape maps contain several landscape element types important for bees but not included in the abovementioned database due to the small scale of these elements. 'Bee-friendly' plant compositions for these landscape element types were obtained by merging information from Baldock et al. (2019), Jachuła et al. (2022), Jachuła et al. (2021), Schmidt et al. (2022), and data from field work

performed within the B-GOOD project. The study by Baldock et al. Baldock et al. (2019) provides information on floral resources of all major land uses in four British cities and was used to define plant composition in residential gardens and allotments, and urban parks. Studies by Jachuła et al. (2022) and Jachuła et al. (2021), investigate floral resources in man-made, non-cropped habitats in agricultural landscapes of SE Poland, and were used to define plant composition in railway embankments, road verges, woodlots and tree rows, fallows, and field margins. The study by Schmidt et al. (2020) analyses vegetation composition of perennial wildflower strips implemented across Saxony-Anhalt in Germany and was used to define plant composition in perennial flower strips, as these were one of the mitigation measures considered within the PoshBee project. Field work performed within the B-GOOD project aimed at determining the plant species composition of specific ALMaSS landscape elements and to confirm/validate the plant composition of some EUNIS habitat types, and was performed in Portugal, the United Kingdom and Belgium.

2.3.4. Implementation of floral resource models in ALMaSS

The pollen and nectar data are formed into three input files, which will be used to generate each landscape element's (LE's) daily pollen and nectar amounts and quality per m². The third file contains the pollen and nectar phenological curve data for crops.

For habitat LE, the floral resource is represented as a community total for the plant community present on the element, which can also be zero for unvegetated elements. For farm field LE, it is a single species depending on the crop at each moment. At any point during the simulation, the element can be queried as to the amount of pollen, nectar, sugar and pollen quality present. The first input file contains the composition of species for each habitat type. The second input file contains the pollen and nectar phenological curve data for all the species in all the habitats.

The pollen and nectar model were implemented based on day degrees. Each day, the plant species accumulate day degrees. Habitat species start to accumulate day degrees from the beginning of each year. Crop species can start to accumulate day degrees from the beginning of each year or the sowing time. Based on the accumulated day degrees on each day, the available floral resource for that day is calculated using the input curves. The floral resource of each habitat type is calculated using the species composition and the resource of each species.

To illustrate the floral resources produced over the whole landscape we have run a 10 year simulation using one landscape in Poland as shown in Figure 14 and Figure 15. As currently calibrated with the flowering plant species that we have so far included, the nectar and pollen resources are limited to spring and summer to provide resources for the bees. For different pollinator species, or if the bees in the model were present for longer periods, the model could include flowers of species that provide resources throughout the year. These pollen and nectar resources are two of the ways that pesticides are also transferred to the bees.

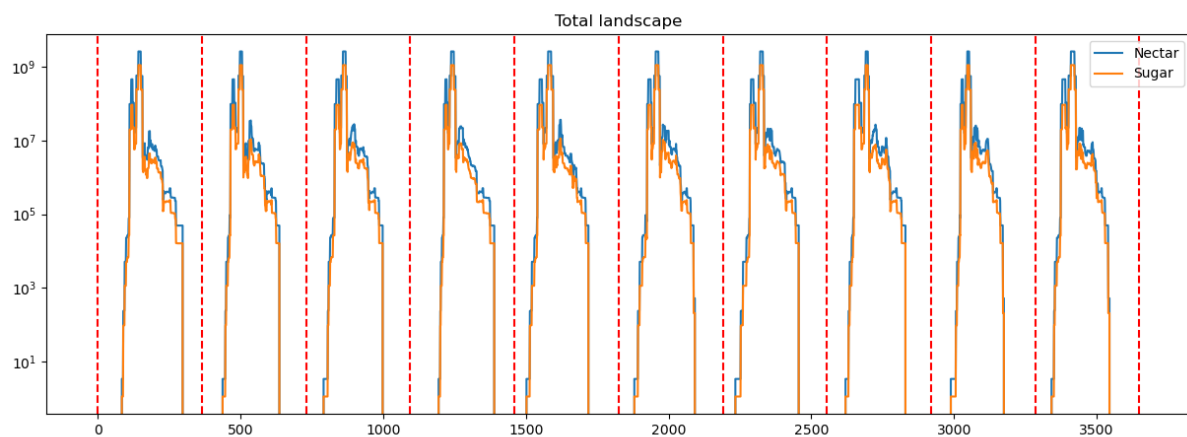


Figure 14. Nectar and sugar resources over 10-years in a 10km-by-10km landscape in Poland. The x-axis is the day in the calendar and y-axis is the resource amount in mg.

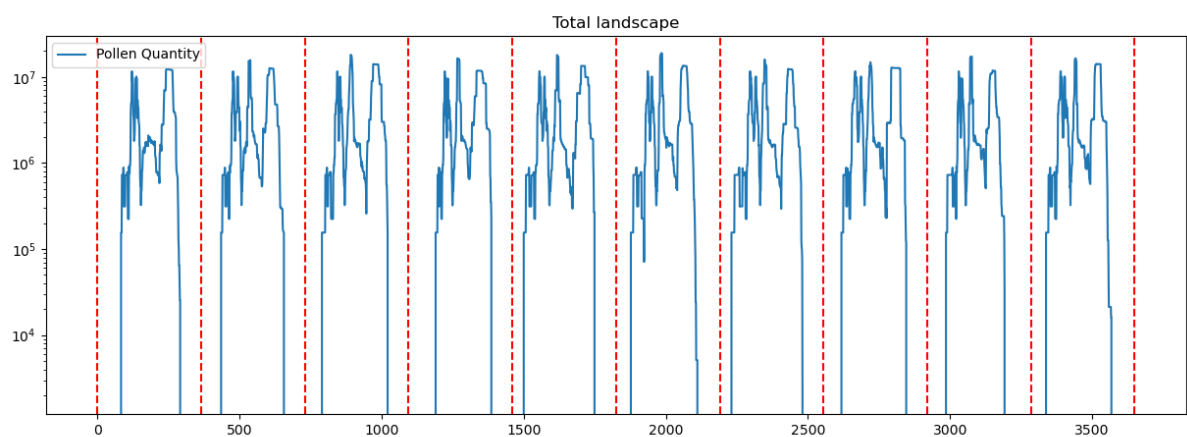


Figure 15. Pollen resources over 10-years in a 10km-by-10km landscape in Poland. The x-axis is the day in the calendar and y-axis is the resource amount in mg.

2.4. Pesticide model

The ALMaSS pesticide model takes into consideration both the applications and the fate of the pesticide. It can handle up to six different pesticide compartments (plant surface, soil, in-plant, pollen, nectar, and seed coating) and the transfer between them is shown in Figure 16.

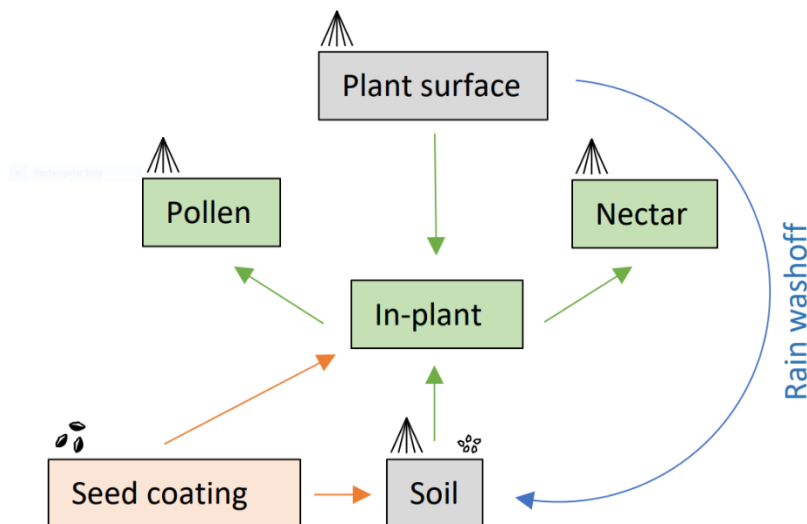


Figure 16. Diagram of transfer between different pesticide compartments. The symbols above each compartment indicate how that compartment can be supplied with pesticide through the application. The pesticides are sprayed onto plant surfaces, soil and directly on to pollen and into nectar, applied as granular formulation to the soil and as a seed coating. The granular formulation is not included in the current phase of development for PoshBee.

A pesticide map is added for each of the compartments per pesticide (compartment maps). The compartment maps can have the same resolution as the landscape or be coarser. In the near future the model will be able to consider up to ten different pesticides simultaneously, and they will each have a unique set of compartment maps. As indicated by the symbols in Figure 16 pesticides can be applied in three different ways: spray, seed coating treatment, and granules treatment. If the pesticide is sprayed, the drift caused by the wind is considered up to ten meters downwind from the spraying point. As agreed with EFSA, we have provided a single use, single product model in line with current EFSA regulation. ALMaSS takes many parameters as input for the pesticide module, which are set using a configuration file. These parameters include the pesticide half-life, water solubility and transfer rates between the different compartments. The EFSA integrated tool makes these parameters available in an easy-to-use format (R Shiny (Chang et al., 2022, Team, 2022)) that will run the model and allow results to be viewed.

3. Bee models

The ALMaSS family of models now has three new bee models, the bumble bee (*Bombus terrestris*), solitary bee (*Osmia bicornis*) and honey bee (*Apis mellifera*) models. These are representative of the three groups of bees, wild eusocial, wild solitary and managed eusocial. The three models were developed separately but use common infrastructure within the ALMaSS framework. They can run separately on common landscapes with nectar and pollen, and pesticide toxicity models. This common infrastructure allows for common scenarios to be run for the three species. Both the *B. terrestris* and *O. bicornis* models include the complete lifecycle of the bees and can be run for multiple years to look at the effect of landscape configuration and management on the population through time. The current version of the ApisRAM model is a single hive model.

3.1. Overview of the *Bombus terrestris* model

We developed the *B. terrestris* model within PoshBee for bumble bee risk assessment. We developed the model in two phases, which are retained in the final model, a captive laboratory model with feeding and controlled temperatures, and a landscape model with bumble bees free to fly in the ALMaSS landscapes, foraging and living out their whole life cycle in repetition over multiple years. The

laboratory model is useful in model calibration, but the landscape model is necessary for performing risk assessment. The model has thus been calibrated as a *B. terrestris* model.



Figure 17. *Bombus terrestris* foraging for pollen north of Aarhus, Denmark on rhododendron.

The landscape model starts at the beginning of the year with a specified number of hibernating gynes. These gynes awake and forage and search for nest sites (Figure 17). The model uses a maximum nest density in each specific habitat (Nagamitsu and Yamagishi, 2009, Darvill et al., 2004, Knight et al., 2005, Rao and Skyrn, 2013, O'Connor et al., 2012, Osborne et al., 2007) and each patch is randomly assigned a density between zero nests and the maximum. Searching gynes check the number of existing colonies and if there is space, found a nest. If the gyne has repeatedly found full patches of habitat she will attempt to steal a colony and her success is determined by the number of workers in the

colony (Cilavdaroglu and Gurel, 2020) and then a 50% chance between the queens. In this way a queen-less colony could also be requeened.

The queen raises the temperature in the nest and lays eggs in clusters (Free and Butler, 1959, Holland, 2013, Ellestad, 2013). The queen and workers when they emerge then incubate the clusters, forage (Figure 17) and feed the larvae in the clusters. As the number of workers in the colony increases the colony switches to producing gynes and males (Knee and Medler, 1965, Shpigler et al., 2013). Gynes and males leave the colony, and they are randomly assigned mates. The individuals avoid inbreeding where there are alternative mates. Males can mate multiple times (up to six times in the current calibration). As well as being subject to normal background mortality, after they have mated for the last time the males die. Gynes forage and search for a hibernation site. If they have sufficient fat stored (an additional 50% of their lean mass) they enter hibernation. They then do not awake until a period of time and a minimum soil temperature is reached. At this point, the cycle repeats when the model is running for more than one year.

The queen and workers forage for nectar and pollen, which they return to the colony. Gynes forage in the solitary phase of their lives for nectar. In both cases this nectar and pollen can be contaminated with pesticides. Larvae are fed a mixture of the nectar and pollen containing pesticides and we have assumed that adults consume some of this while doing so. Workers, gynes and the queen also consume some of the nectar while foraging. Inside the colony all adults also consume nectar from the colony stores. These are the main way that pesticides make their way into the bumble bees. Bees can also be exposed to pesticides through overspray while out in the landscape. This pesticide degrades in transport and storage in nectar and pollen, when held by larvae, in the stomach of the bees and once it has entered the bees' system. The quantity of pesticide in the bees' system in relation to the size of the bee increases the probability of the bee dying.

3.2. Overview of the *Osmia bicornis* model

The ALMaSS *O. bicornis* model has been developed within the project "Beneficial insects in agricultural landscape: modelling effect of pesticides and landscape structure" funded by the National Science Centre, Poland (project no. 2015/19/B/NZ8/01939) and within the EcoStack project (European Union's Horizon 2020 research and innovation program, grant agreement no. 773554). It aims to provide a realistic and detailed representation of *O. bicornis* populations in space and time in European agricultural landscapes. During the simulation, each bee (at different developmental stages) is represented as an agent in a specific behavioural state (e.g., developing, dispersing, reproducing). The model is spatially explicit, and both the position of a bee and its nest in the landscape are simulated. During its activities, the bee interacts with the landscape model, e.g., through temporally dynamic weather, vegetation, or floral resources.

The parameters of the model are based on field and laboratory data on *O. bicornis* available in the literature and from experiments carried out by the Terrestrial Ecosystems and Ecotoxicology Group, Institute of Environmental Sciences, Jagiellonian University in Kraków, Poland (Figure 18). When the necessary data were not available for *O. bicornis*, parameters were estimated based on published data from other species of the *Osmia* genus with similar life history (*O. cornuta*, *O. cornifrons*, and *O. lignaria*). Calibration of the model included fitting (i) time for in-nest development for all stages, (ii) species phenology (flight period), (iii) distribution of eggs per nest, and (iv) emergence weight of adult female *O. bicornis*.



Figure 18. *O. bicornis* in one of the pesticide experiments performed by the Terrestrial Ecosystems and Ecotoxicology Group, Institute of Environmental Sciences, Jagiellonian University in Kraków, Poland.

The development of *O. bicornis* can be divided into six main life stages: egg, larva, prepupa, pupa, cocooned adult, and adult. The model takes into account the behaviour of all bee life stages on a daily basis. The life stages from egg to cocooned adult take place inside the nest. Egg laying and larval development occur in spring, while prepupal and pupal stages occur in summer. The imago instar appears in the cocoon at the end of summer/beginning of autumn. The duration of in-nest development is temperature dependent, with higher temperatures resulting in faster development of eggs, larvae and pupae. This is implemented using a simple degree-day model. The relationship between prepupal duration and temperature is non-linear. The highest rates of prepupal developmental are achieved at intermediate temperatures. The cocooned adult is the overwintering form of the red mason bee. The overwintering period of *O. bicornis* is divided into three parts: pre-wintering, diapause, and post-diapause quiescence. The temperature conditions during pre-wintering influence the overwintering mortality of the bees, while the temperature conditions during diapause influence the time of emergence of the bees from the nest in spring (so the warmer the winter, the earlier the bees emerge).

Only adults interact with the local landscape/environment after emerging from the cocoon. The model assumes that all adult females are fertilised, so mating activity is not modelled. Males are not included in the model except for the nesting and provisioning activities of the mother. Each female bee after emergence from the nest is given a mass property as a direct function of the mass of provision available in the nest cell from which the bee originates. Bee mass is an important trait because it influences the reproductive potential of the bee, i.e., larger bees are generally able to lay more eggs and the sex ratio of their offspring is more skewed towards females.

After emergence and the pre-nesting period female bees enter the reproductive phase and start looking for nesting sites. Female *O. bicornis* use pre-existing cavities, usually tube-shaped, to build their nests (such as dry stems of hollow plants, or dead wood). Nesting density in a landscape is given

as the number of available nests per one m² of each landscape element in the land cover map. A minimum and maximum nest density is defined for each type of landscape element, and the actual nest density of a landscape element is determined from this range of values at the start of each simulation. When moving, the bee is able to access information about whether a nest is available at its current location. The brood cells in the nest are arranged linearly in series with transverse partitions in between. In each nest, fertilized eggs (daughters) are always laid first, followed by unfertilized ones (sons). A mother bee builds a separate brood cell for each egg, which she provisions with pollen and a small amount of nectar. In the current version of the model, it is assumed that nectar is not a limiting factor for *O. bicornis*, so only pollen resources and the search for pollen are considered. For each nest to be created, a female bee first develops a 'plan' for laying eggs, which includes determining number of eggs in a nest, their sex ratio (i.e., number of female and male eggs), and target provisions for each of the planned eggs. The 'plan' can only be achieved if there are optimal (favourable) environmental conditions, i.e., if there are no restrictions on floral (pollen) resources around the nest and weather conditions allow for a constant supply. However, if floral resources are sub-optimal and/or the weather is bad (too cold, too rainy or too windy), the amount of provision that can be collected may be less than planned, and the number and mass of offspring produced may be less.

In the model, bees can die because they have finished laying all their planned eggs, because they have reached the end of their lifespan or because of external events. Mortality due to external, unknown factors is defined separately for the stages from egg to pupa, hibernation and adult bees outside the nest. In addition, bees can be killed by parasitoids living in their nests. Only open cell parasitism is included in the model, so that the longer the brood cell is open, the higher the probability of parasitism.

The model *Osmia bicornis* can be exposed to pesticides through foraging activities. The larvae are killed based on a user-defined threshold and the pesticide amount in the pollen that the mother put into the nest. The females are killed based their pesticide body burden as explained in Section 3.5.

3.3. Overview of the *Apis mellifera* (ApisRAM) model

ApisRAM (Duan et al., 2022) has been funded by EFSA and developed to the specifications of the MUST-B working group and EFSA following their scientific opinion on the Healthy-B toolbox (Welfare, 2016). The final version of ApisRAM is expected to be ready for more complete environmental risk assessment in 2027.

The ApisRAM model uses a spatially explicit individual-based approach for honey bees both as foragers in the landscape and for bees within the hive. The goal of ApisRAM is to provide a framework for virtual experiments to explore the effects of combined stressors on honey bee hives. To do this, there are five interconnected modules in ApisRAM, namely development, activities, thermodynamics, biological agents and bee keeping management practice.

For the current version of ApisRAM, three castes of honey bees (worker, drone and queen) are modelled. With the exception of the queen, workers and drones develop according to the full life cycle of the honey bee, the egg, larva, pupa, and adult. The adults then remain as the kind of adult they develop into until they die. The queen is present as an already mated adult in the model when the simulation starts. If the queen dies within the simulation, we assume that the hive is dead. In the development module, stress caused by nutrition is calculated based on the amount of food eaten compared with the required food.

In the activity module, the queen only has one activity to perform, which is to lay eggs in the appropriate empty cells when it is warm enough. The drones only consume resources in the hive without doing anything else. The worker bees are the busiest ones in the hive. The workers are constantly monitoring the needs of the nest and then performing those tasks. These tasks can for example include brood care, guarding, cleaning and foraging to mention only a few (Figure 19).



Figure 19. Early spring honey bee foraging for pollen on common box (*Buxus sempervirens*) north of Aarhus, Denmark.

Temperature influences the behaviour of individual bees and the decisions that they make. Therefore, modelling temperature distribution inside the hive and within the bees' body has been crucial to properly simulate honey bee behaviour. In the thermodynamics module of ApisRAM, a three-dimensional matrix tracks the temperature of each cell of the frames in the hive. Convolutional operations are used to model the heat exchange between the bees and the cells, and between the hive and the environment. When the bee's body temperature deviates from its optimal value, it will be stressed by the temperature.

When the model bees forage in the landscape, they can be exposed to pesticides by contact with the treated plants and through overspray. They can also take contaminated pollen or nectar back to the hive. After they take the contaminated pollen and/or nectar to the hive, the model tracks the pesticide concentration at the cell level in the hive. The effect of pesticides is modelled as the stress they cause on the bees. Besides these lethal effects we have also modelled sublethal effects, including the homing ability of foragers, reduced reproductive performance of the queen, and reduced hypopharyngeal gland development.

In the biological agent module, we have included Varroa, *Nosema*, Deformed Wing Virus (DWV) and Acute Bee Paralysis Virus (ABPV). Both the stress caused by pesticide and biological agents can cause damage to the bee's immune system strength which interacts with its vitality rate. Furthermore, all four types of stressors, nutritional state, body temperature, pesticides and biological agents, are connected through vitality. In other words, they are not independent but interacting with each other. For example, when the bee is in a good state of nutrition and has an appropriate body temperature, its vitality value will increase which can help it recover from the stress caused by pesticides and biological agents, for example.

In the bee keeping practice module, several management practices can be applied at a specific time, which is defined in an external file. For example, 'killing Varroa' can be applied to the hive. After this, a certain proportion of the Varroa in the hive will be killed.

3.4. Overview of the pesticide toxicity model

All three bee models use the same base pesticide toxicity model, which is implemented as part of ALMaSS. The implementation supports up to ten pesticide types, of which the number is decided by the setting in the pesticide engineer. If more than two types of pesticide are used in the pesticide engine, an additive effect is assumed for multiple pesticide use, i.e., the total amount of all pesticides is used to calculate the pesticide impact. The pesticide impact is implemented using the general unified threshold model for survival (GUTS) (Ashauer et al., 2015) model as default as this has been adopted by EFSA as a method in the regulatory risk assessment of pesticides for aquatic species (EFSA opinion on TKTD models, 2018), but other models can be implemented.

Three exposure paths are included for the bees, intake, contact and overspray. The intake pathway happens when model bees eat or are fed with the contaminated flower resource. The amount of pesticide within the consumed resource accumulates in the bee's body. When bees forage and come into contact with the contaminated plant surface, a certain proportion of pesticide on the plant surface will be transferred to the bee. The transferred amount is controlled by a user-defined parameter. When a bee is flying in a field where a pesticide is being sprayed, there is a chance that the bee is over-sprayed by the pesticide. Once contaminated by pesticides, the pesticide body burden will decay according to the pesticide half-life. The mortality rate caused by the pesticide body burden is updated every day, which is used to calculate the chance of death due to pesticides.

4. ERA modelling tool interface

The user interface is a means of allowing users to run the ALMaSS models for the three bee species. The user can choose the species and duration in years, and then the scenarios and locations to compare. As the models can be time consuming to run, the outputs of the models will be saved, and the user can then choose which scenarios to compare (including those previously run). The user can specify whether landscapes have flower strips and pesticides in the landscape or not. The user has full

control over the setting for pesticides. These settings include which crops pesticides are applied to, how, and the half-life of these products.

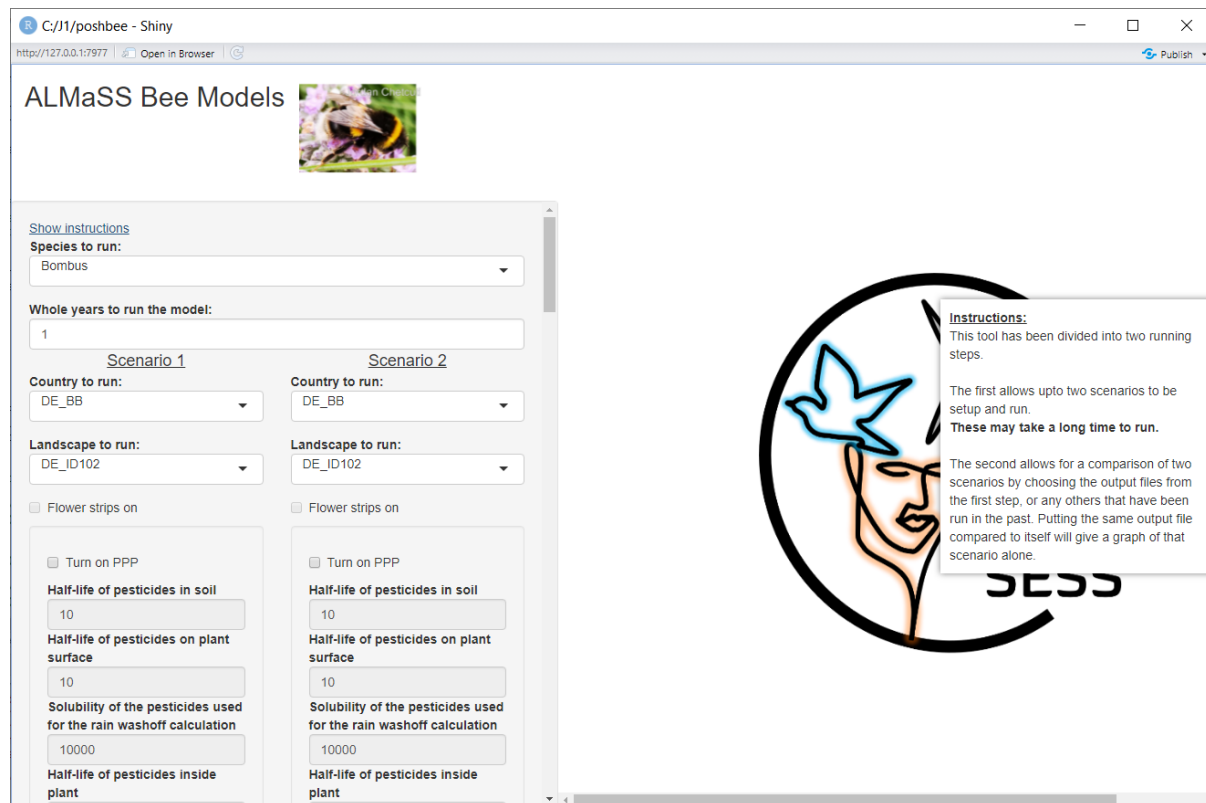


Figure 20. Shiny R interface allowing the model scenarios to be set up and run.

The interface has been created as an R Shiny application ((Chang et al., 2022), Figure 20) and deployed as a docker image. Upon starting the application, the user can setup up to two scenarios which, when started, will run in parallel. We strongly encourage that the outputs of new scenarios are given new unique file names. In this way the user can accumulate a series of past run scenarios which can then be compared within the application by selecting them at the bottom to compare. This also means that the model does not have to be run within a session to be able to compare scenarios. The comparison will show the two scenarios as separate lines and show all of the life stages for each species (Figure 21). For *Bombus terrestris* these are the colony, clusters of juveniles, eggs, larvae, pupae, workers, gynes, males and queens. For *Osmia bicornis*, eggs, larvae, pre-pupae, pupae, cocoons and the females. And finally, for *Apis mellifera*, worker eggs, worker larvae, worker pupae, worker adults, drone eggs, drone larvae, drone pupae, drone adults and queens. In general, it is most common that the user will compare within species, but to allow an eventuality where the user may either accidentally or intentionally wish to compare between species, the life stages have been prefixed with a letter representing the species. The prefix letters are B, O and A for *Bombus*, *Osmia* and *Apis* respectively.

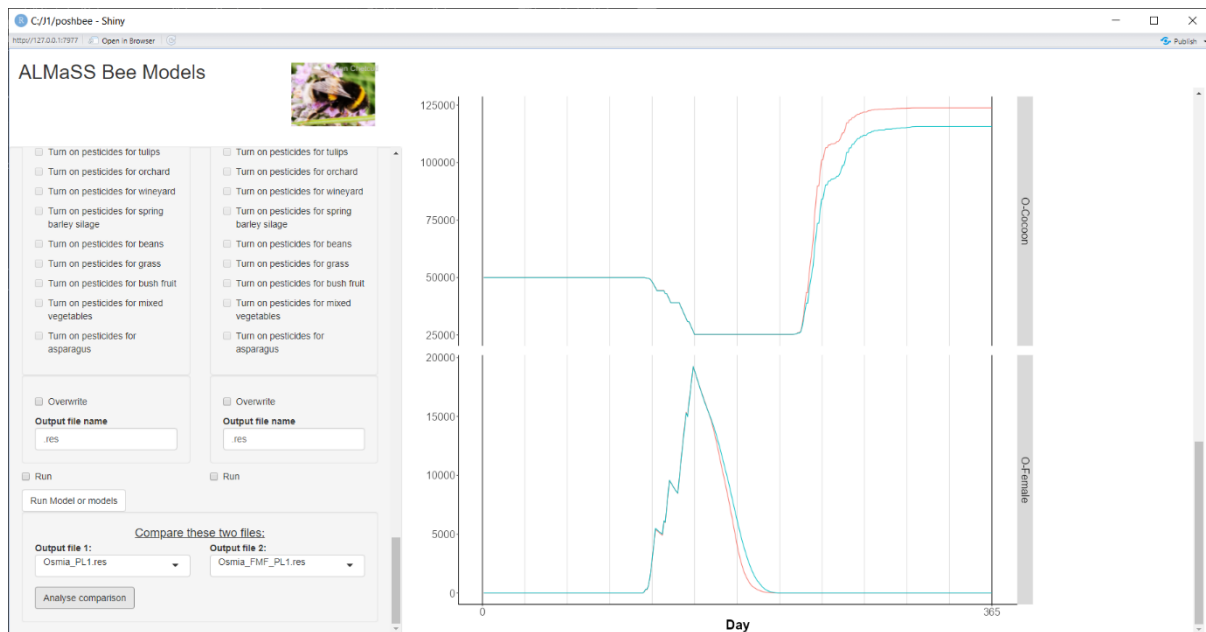


Figure 21. Example of a comparison of two scenarios on the same landscape for *Osmia bicornis*.

5. Example Scenarios

To run simulations for ERA purposes, baseline and test scenarios need to be defined. An example could be testing the effect of plant protection products (PPPs) (commonly termed pesticides). A single product (i.e., type of pesticide) was used in this tool. Afterwards the results of each scenario can be compared with the baseline and/or each other to assess the impact of pesticides under different scenarios.

5.1. Pesticide impact

5.1.1. Scenario description

The ALMaSS landscape model has a crop management module in which crops are managed according to the Good Agricultural Practices (GAP). The farms are classified into different types. Each type has its own crop rotation plan for each modelled country. Based on these, we used two settings of crop rotations (L1 and L2) in the example scenarios:

L1: Normal crop rotation.

The ALMaSS landscape models run with the normal crop rotations for each country. This is the most realistic situation.

L2: Monoculture crop.

Here, all the farms are set to only grow winter rape in their fields. This is an extreme case where we can evaluate a worst-case scenario for bees when the crops are applied with pesticide as winter rape can provide a large amount of floral resources.

For each of the above landscape models, two types of pesticide application were used, spray and seed coating. Spray is the most common application type. The spray time plays a key role in the impact on bees. If it is applied after the flowering period of the target crop, the impact on bees is very limited unless drifts contaminate the floral resource surrounding the targeted fields. Seed coating might have more serious impacts on the bees through the pathway of the plant itself since the plants are contaminated just after the seeds are sowed. Furthermore, the pesticide can stay in the soil for a long

time and might contaminate the plants in the next season. Three pesticide combinations can be assessed, using only spray, using only seed coating, or using both.

Based on the above considerations, the final scenarios consist of two baseline scenarios and six test scenarios:

Baseline scenarios

1. Baseline scenario 1 uses L1 (normal crop rotation) landscape models without any pesticide use.
2. Baseline scenario 2 uses L2 (monoculture crop) landscape models without any pesticide use.

Test scenarios

1. Test scenario 1 uses L1 landscape models with all crops being treated with pesticide spray applications following GAP.
2. Test scenario 2 uses L1 landscape models with all crops being treated with seed coating before sowing.
3. Test scenario 3 uses L1 landscape models with all crops being treated with both seed coating and pesticide spray applications following GAP.
4. Test scenario 4 uses L2 landscape models with all crops being treated with pesticide spray applications following GAP.
5. Test scenario 5 uses L2 landscape models with all crops being treated with seed coating before sowing.
6. Test scenario 6 uses L2 landscape models with all crops being treated with both seed coating and pesticide spray applications following GAP.

5.1.2. Indicative results

We have run *Osmia bicornis* simulations using a landscape from Poland for all the baseline and test scenarios. The simulations run for 20 years. The number of *O. bicornis* female adults per day for the last 10 years can be found in Figure 22 and Figure 23. Please note the *O. bicornis* model has not been fully calibrated and the pesticide engine and pesticide toxicity model have not been parametrised properly. This is only a show-case example but without any meaningful indications about the pesticide impacts.

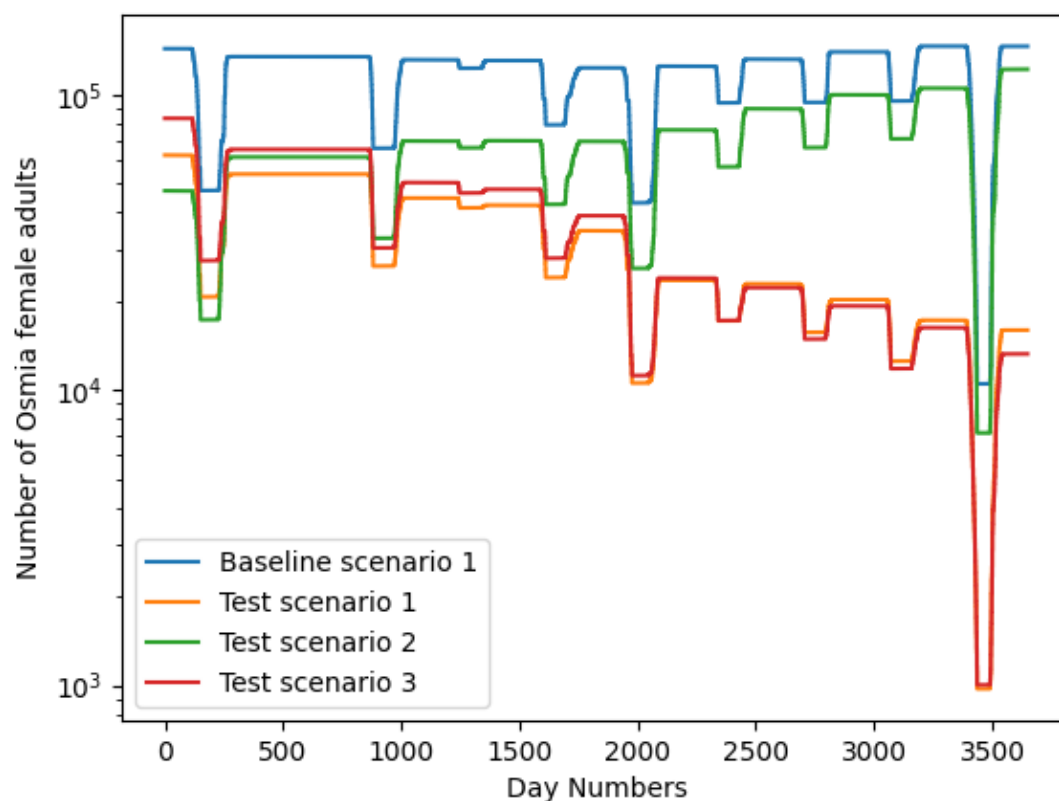


Figure 22. Number of *Osmia bicornis* female adults in 10-years simulation for four scenarios using crops in rotation

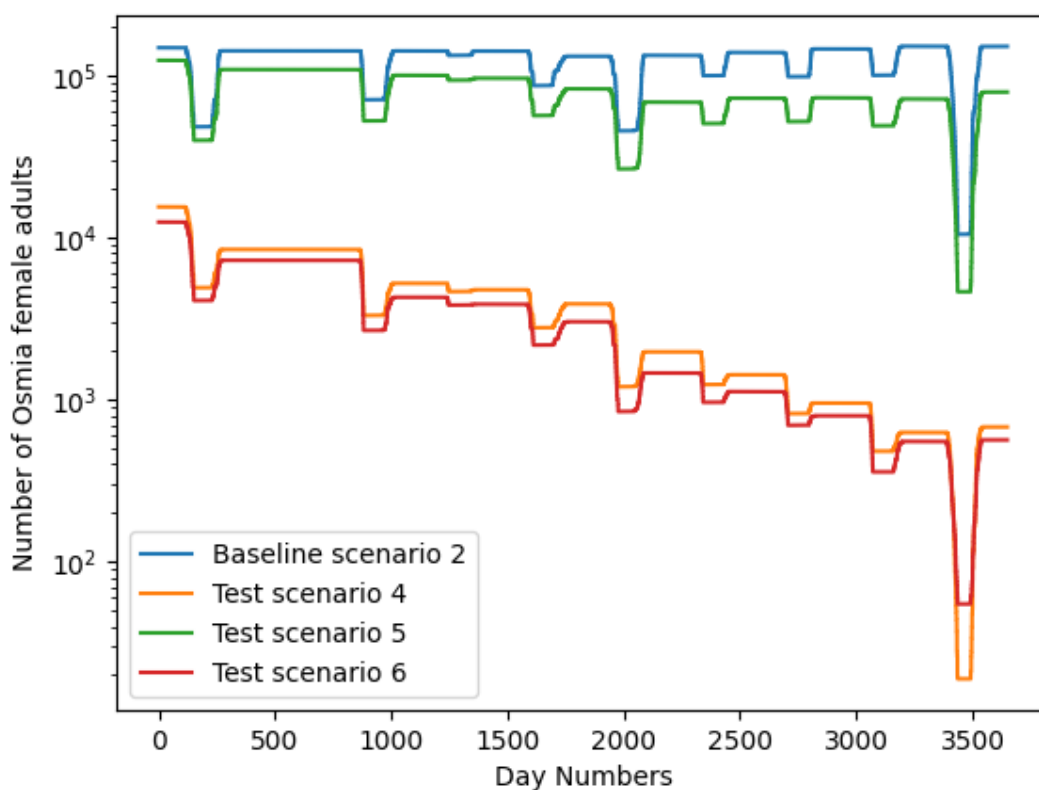


Figure 23 Number of *Osmia bicornis* female adults in 10-years simulation for four scenarios using monoculture crop

5.2. Mitigation measure

The landscape models were introduced with one artificial mitigation manipulation consisting of creating flower strips as field margins around crops (Figure 24). The flower strips, with a width of six meters, were not treated when the crops were applied with pesticide, which made it a measure to mitigate the risk caused by intended pesticide usage.

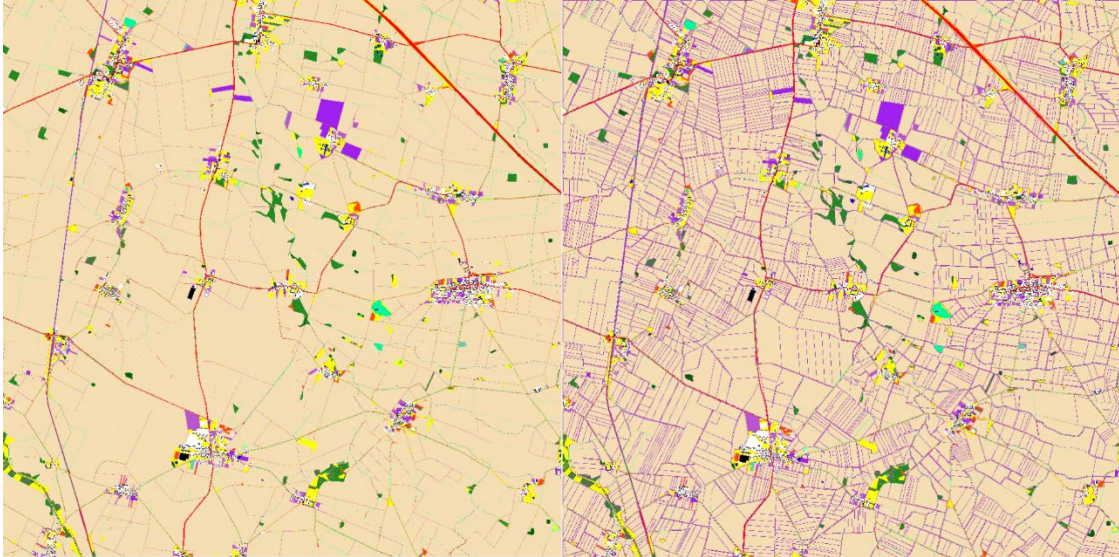


Figure 24. The original landscape without flower strips on the left and a landscape showing the flower strips appearing as purple lines around the farm fields.

We have also run *Osmia bicornis* simulations for 20 years using a landscape with flower strips in Poland. The number of *O. bicornis* female adults per day for the last 10 years can be found in Figure 25 and Figure 26.

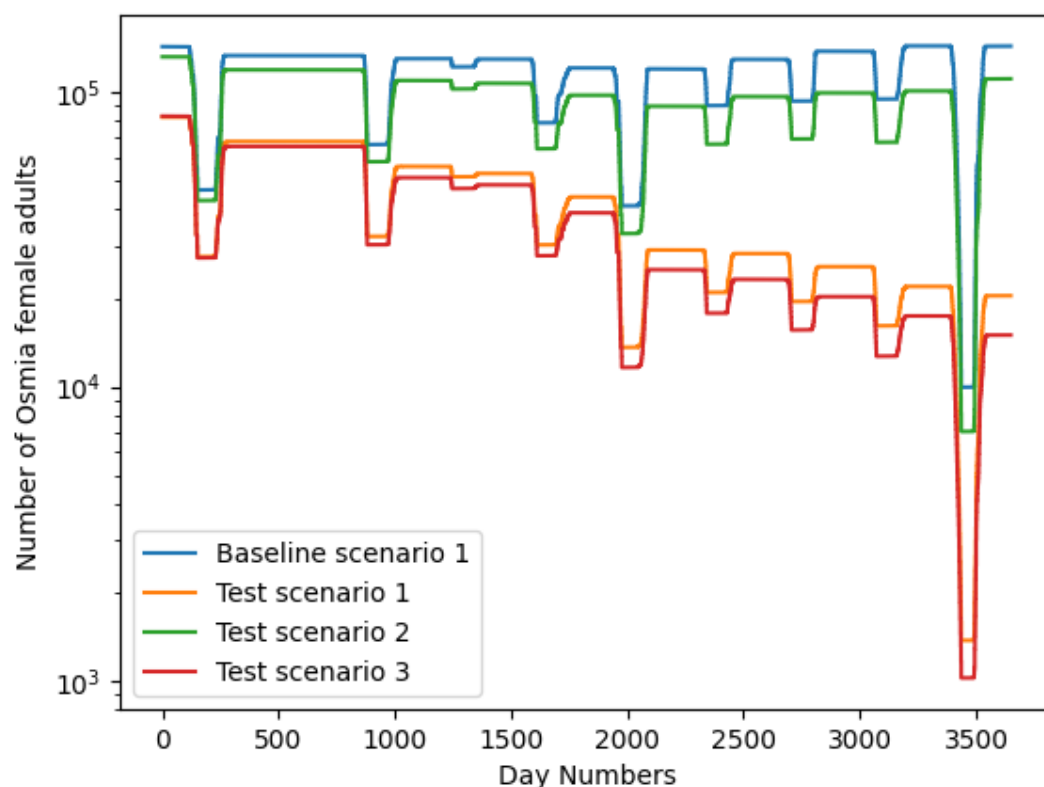


Figure 25 Number of *Osmia bicornis* female adults in 10-years simulation for four scenarios using crops in rotation with flower strips

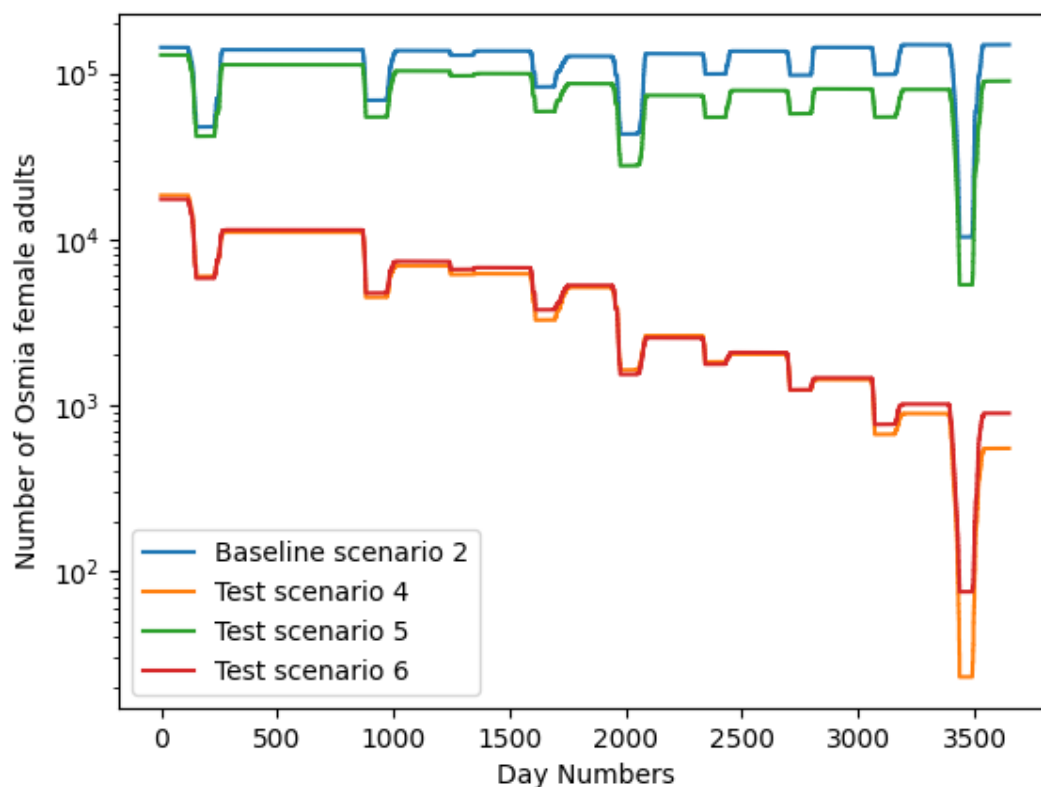


Figure 26 Number of *Osmia bicornis* female adults in 10-years simulation for four scenarios using monoculture crop with flower strips

6. Description of the content of the digital delivery

Here we include the ERA modelling tool for wild and managed bees which we have made ready for EFSA use. This takes the form of a R Shiny application front end to run ALMaSS scenarios for *Bombus terrestris*, *Osmia bicornis* and *Apis mellifera*. This Shiny application is deployed in two ways, as a hosted web-interface and using the software Docker. The web version can be found at: <https://app-poshbee.cloud.sdu.dk/>. The Docker software provides a container that can be setup to provide every user with the same working environment on their own machine. Once installed and set up the user can then run the interface in their browser. Below are the instructions for setting up docker and the Shiny interface and then starting the application.

6.1. Instructions for setting up and starting Docker and Shiny.

Please follow the steps below to set up the Docker image, we assume that you are using a Windows machine.

6.1.1. Installing docker and ALMaSS PoshBee image:

This only needs to be done once for a computer. After this is done, please refer to Section 6.1.2 for the use of the docker image for running simulations.

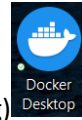
1. Follow steps a, b, and c to install WSL.
 - a. Open PowerShell or Windows Command Prompt in administrator mode and run the following command: `wsl --install`
 - i. You will be asked to set up a UNIX username. Enter one that is all lowercase letters.
 - ii. You will be asked to set a password. This can include capitals and special characters.
 - b. Restart your computer.
 - c. In case of problems see more in the documentation from Microsoft: <https://learn.microsoft.com/en-us/windows/wsl/install>
2. Download and install the Docker Desktop from the link below. <https://www.docker.com>
3. Follow steps a, and b to Download and unzip the PoshBee docker image:
 - a. Click the link: https://gitlab.com/ALMaSS/almass_docker.
 - b. Download the folder “poshbee” which contains two files (using the download button next to the clone button)
 - c. Unzip the file (right click “Extract All...”). This folder contains two files “Dockerfile” and “02_set_almass.sh”. The folder is only needed during installation.
4. Follow step a-d to build ALMaSS using the docker image:



- a. Start “Docker Desktop”
- b. Open PowerShell or Windows Command Prompt.
- c. Change the directory using the “cd” command followed by a space and the pathway to where the poshbeer was unzipped in step 3b (for example: “cd C:\Users\me\Downloads\almass_docker-main-poshbee\almass_docker-main-poshbee\poshbee”).
- d. Run the command (copy paste the line below):
`docker build -t almass/poshbee ./`

6.1.2. Running ALMaSS PoshBee docker image

Please follow the steps below to start the Docker container to run simulations.



1. Start “Docker Desktop” (if not already running)
2. Open PowerShell or Windows Command Prompt (if not already running) and run the command below:
 - a. `docker run --rm -ti --user root -p 3838:3838 almass/poshbee`
 - b. This make take a few moments while the code is downloaded and checked.
3. Launch a browser, go to the address below.
 - a. <http://localhost:3838/poshbee/>

7. Conclusion

The ERA modelling tool for wild and managed bees, developed within the ALMaSS modelling framework, includes three agent-based models to simulate the impacts of landscape management and pesticide use on bee populations. These models were designed to meet the demand for a tool that can help assess the risks posed by pesticides to bees in various landscape scenarios.

The tool's interface allows users to select from three bee species, several selected countries each with ten landscapes, as well as running different scenarios of pesticide application or adding measures aimed and assumed to support non-target arthropods, such as flower strips. This flexibility enables users to explore different scenarios and evaluate the impacts of pesticides on bee populations in a variety of settings. The ALMaSS system includes a floral resource model and a complex fate pesticide model, which considers the impacts of pesticides on bees through different exposure pathways. This allows for a comprehensive assessment of the risks posed by pesticides to bee populations.

By providing a means to evaluate the impacts of pesticides on wild and honey bees, the ERA modelling tool has the potential to inform policy decisions related to the management of pesticides and their impacts on bee populations. We hope that this tool will show what is possible in the development of tools to better understand the risks posed by pesticides to bee populations, other pollinator and non-target arthropods and we hope this will lead to further development of all three bee models to improve the biological realism and make an effective tool that can easily be used by stakeholders.

8. Acknowledgements

The *Bombus terrestris* model received funding from the European Horizon 2020 research and innovation program under grant agreement no. 773921 (PoshBee). The *Osmia bicornis* model development was supported by the National Science Centre, Poland (project no. 2015/19/B/NZ8/01939) and the European Union's Horizon 2020 research and innovation program, (EcoStack project; grant agreement no. 773554). ApisRAM is under development supported by EFSA through contracts OC/EFSA/SCER/2016/03 and GP/EFSA/SECR/2021/02. We would like to acknowledge the wider ALMaSS group for help given and many years of development on ALMaSS architecture on which the bee, landscape, floral resource, and pesticides rely. We would also like to express our appreciation to OpenAI for providing us with access to ChatGPT which we used as a drafting and proofing tool in this report.

9. References

- ASHAUER, R., O'CONNOR, I., HINTERMEISTER, A. & ESCHER, B. I. 2015. Death Dilemma and Organism Recovery in Ecotoxicology. *Environmental Science & Technology*, 49, 10136-10146.
- BALDOCK, K. C. R., GODDARD, M. A., HICKS, D. M., KUNIN, W. E., MITSCHUNAS, N., MORSE, H., OSGATHORPE, L. M., POTTS, S. G., ROBERTSON, K. M., SCOTT, A. V., STANICZENKO, P. P. A., STONE, G. N., VAUGHAN, I. P. & MEMMOTT, J. 2019. A systems approach reveals urban pollinator hotspots and conservation opportunities. *Nature Ecology & Evolution*, 3, 363-373.
- BUCZKOWSKA, H. & KOWALSKA, G. 2000. Effect of pollination by bumble bees (*Bombus terrestris*) on yields of aubergine grown in a plastic tunnel. *Annales Universitatis Mariae Curie-Skłodowska. Sectio EEE, Horticultura*, 8, 383-389.
- CHANG, W., CHENG, J., ALLAIRE, J. J., SIEVERT, C., SCHLOERKE, B., XIE, Y., ALLEN, J., MCPHERSON, J., DIPERT, A. & BORGES, B. 2022. shiny: Web Application Framework for R.
- CILAVDAROGLU, E. & GUREL, F. 2020. Effect of requeening on colony development in the bumble bee, *Bombus terrestris*. *Journal of Apicultural Research*, 0, 1-5.
- DARVILL, B., KNIGHT, M. E. & GOULSON, D. 2004. Use of genetic markers to quantify bumblebee foraging range and nest density. *OIKOS*, 107, 471-478.
- DUAN, X., WALLIS, D., HATJINA, F., SIMON-DELSON, N., BRUUN JENSEN, A. & TOPPING, C. J. 2022. ApisRAM Formal Model Description. *EFSA Supporting Publications*, 19, 7184E.
- Bumblebee queen laying eggs - YouTube*, 2013. Directed by ELLESTAD, M.
- ESRI 2020. ArcGIS Desktop: Release 10.8.1.
- FILIPIAK, Z. M., DENISOW, B., STAWIARZ, E. & FILIPIAK, M. 2022. Unravelling the dependence of a wild bee on floral diversity and composition using a feeding experiment. *Science of The Total Environment*, 820, 153326.
- FREE, J. B. & BUTLER, C. G. 1959. *Bumblebees (Collins New Naturalist Library, Book 40)*.
- HOLLAND, J. G. 2013. *Colony Life History in the Bumble Bee Bombus terrestris: Interactions, Timing and Control*.
- JACHUŁA, J., DENISOW, B. & WRZESIEŃ, M. 2021. Habitat heterogeneity helps to mitigate pollinator nectar sugar deficit and discontinuity in an agricultural landscape. *Science of The Total Environment*, 782, 146909-146909.
- JACHUŁA, J., DENISOW, B., WRZESIEŃ, M. & ZIÓŁKOWSKA, E. 2022. The need for weeds: Man-made, non-cropped habitats complement crops and natural habitats in providing honey bees and bumble bees with pollen resources. *Science of The Total Environment*, 840, 156551.
- KNEE, W. J. & MEDLER, J. T. 1965. The Seasonal Size Increase of Bumblebee Workers (Hymenoptera: *Bombus*). *The Canadian Entomologist*, 97, 1149-1155.
- KNIGHT, M. E., MARTIN, A. P., BISHOP, S., OSBORNE, J. L., HALE, R. J., SANDERSON, A., GOULSON, D., SANDERSON, R. A. & GOULSON, D. 2005. An interspecific comparison of foraging range and nest density of four bumblebee (*Bombus*) species. *Molecular Ecology*, 14, 1811-1820.
- MCKINNEY, W. & OTHERS 2010. Data structures for statistical computing in python. *Proceedings of the 9th Python in Science Conference*.
- NAGAMITSU, T. & YAMAGISHI, H. 2009. Nest density, genetic structure, and triploid workers in exotic *Bombus terrestris* populations colonized Japan. *APIDOLOGIE*, 40, 429-440.
- O'CONNOR, S., PARK, K. J. & GOULSON, D. 2012. Humans versus dogs; a comparison of methods for the detection of bumble bee nests. *JOURNAL OF APICULTURAL RESEARCH*, 51, 204-211.
- OSBORNE, J. L., MARTIN, A. P., SHORTALL, C. R., TODD, A. D., GOULSON, D., KNIGHT, M. E., HALE, R. J. & SANDERSON, R. A. 2007. Quantifying and comparing bumblebee nest densities in gardens and countryside habitats. *Journal of Applied Ecology*, 45, 784-792.
- OVASKAINEN, O., MEYKE, E., LO, C., TIKHONOV, G., DELGADO, M. D. M., ROSLIN, T., GURARIE, E., ABADONOVA, M., ABDURAIMOV, O., ADRIANOVA, O., AKIMOVA, T., AKKIEV, M., ANANIN, A., ANDREEVA, E., ANDRIYCHUK, N., ANTIPIN, M., ARZAMASCEV, K., BABINA, S., BABUSHKIN, M., BAKIN, O., BARABANCOVA, A., BASILSKAJA, I., BELOVA, N., BELYAEVA, N., BESPALOVA, T., BISIKALOVA, E., BOBRETISOV, A., BOBROV, V., BOBROVSKYI, V., BOCHKAREVA, E., BOGDANOV,

- G., BOLSHAKOV, V., BONDARCHUK, S., BUKHAROVA, E., BUTUNINA, A., BUYVOLOV, Y., BUYVOLOVA, A., BYKOV, Y., CHAKHIREVA, E., CHASHCHINA, O., CHERENKOVA, N., CHISTJAKOV, S., CHUHONTSEVA, S., DAVYDOV, E. A., DEMCHENKO, V., DIADICHEVA, E., DOBROLYUBOV, A., DOSTOYEVSKAYA, L., DROVNINA, S., DROZDOVA, Z., DUBANAEV, A., DUBROVSKY, Y., ELSUKOV, S., EPOVA, L., ERMAKOVA, O. S., ERMAKOVA, O., ESENGELDENOVA, A., EVSTIGNEEV, O., FEDCHENKO, I., FEDOTOVA, V., FILATOVA, T., GASHEV, S., GAVRILOV, A., GAYDYSH, I., GOLOVCOV, D., GONCHAROVA, N., GORBUNOVA, E., GORDEEVA, T., GRISHCHENKO, V., GROMYKO, L., HOHRYAKOV, V., HRITANKOV, A., IGNATENKO, E., IGOSHEVA, S., IVANOVA, U., IVANOVA, N., KALINKIN, Y., KAYGORODOVA, E., KAZANSKY, F., KISELEVA, D., KNORRE, A., KOLPASHIKOV, L., KOROBOK, E., KOROLYOVA, H., KOROTKIKH, N., KOSENKOV, G., KOSSENKO, S., KOTLUGALYAMOVA, E., KOZLOVSKY, E., KOZSHEECHKIN, V., KOZURAK, A., KOZYR, I., KRASNOPEVTSEVA, A., KRUGLIKOV, S., KUBERSKAYA, O., KUDRYAVTSEV, A., KULEBYAKINA, E., KULSHA, Y., KUPRIYANOVA, M., KURBANBAGAMAEV, M., et al. 2020. Chronicles of nature calendar, a long-term and large-scale multitaxon database on phenology. *Scientific Data*, 7.
- RAILSBACK, S. F. & GRIMM, V. 2017. *An Agent-Based and Individual-Based Modelling: A practical introduction*.
- RAO, S. & SKYRM, K. M. 2013. Nest Density of the Native Bumble Bee, *Bombus nevadensis* Cresson (Hymenoptera: Apoidea), in an Agricultural Landscape. *JOURNAL OF THE KANSAS ENTOMOLOGICAL SOCIETY*, 86, 93-97.
- SCHMIDT, A., FARTMANN, T., KIEHL, K., KIRMER, A. & TISCHEW, S. 2022. Effects of perennial wildflower strips and landscape structure on birds in intensively farmed agricultural landscapes. *Basic and Applied Ecology*, 58, 15-25.
- SCHMIDT, A., KIRMER, A., KIEHL, K. & TISCHEW, S. 2020. Seed mixture strongly affects species-richness and quality of perennial flower strips on fertile soil. *Basic and Applied Ecology*, 42, 62-72.
- SHPIGLER, H., TAMARKIN, M., GRUBER, Y., POLEG, M., SIEGEL, A. J. & BLOCH, G. 2013. Social influences on body size and developmental time in the bumblebee *Bombus terrestris*. *Behavioral Ecology and Sociobiology*, 67, 1601-1612.
- TEAM, R. C. 2022. R: A Language and Environment for Statistical Computing. Vienna, Austria.
- TEMPL, B., KOCH, E., BOLMGREN, K., UNGERSBÖCK, M., PAUL, A., SCHEIFINGER, H., RUTISHAUSER, T., BUSTO, M., CHMIELEWSKI, F.-M., HÁJKOVÁ, L., HODZIĆ, S., KASPAR, F., PIETRAGALLA, B., ROMERO-FRESNEDA, R., TOLVANEN, A., VUČETIČ, V., ZIMMERMANN, K. & ZUST, A. 2018. Pan European Phenological database (PEP725): a single point of access for European data. *International Journal of Biometeorology*, 62, 1109-1113.
- TOPPING, C. J., DALBY, L. & SKOV, F. 2016. Landscape structure and management alter the outcome of a pesticide ERA: Evaluating impacts of endocrine disruption using the ALMaSS European Brown Hare model. *Science of the Total Environment*, 541, 1477-1488.
- TOPPING, C. J., HANSEN, T. S., JENSEN, T. S., JEPSEN, J. U., NIKOLAISEN, F. & ODDERSKÆR, P. 2003. ALMaSS, an agent-based model for animals in temperate European landscapes. *Ecological Modelling*, 167, 65-82.
- TOPPING, C. J., HØYE, T. T. & OLESEN, C. R. 2010. Opening the black box-Development, testing and documentation of a mechanistically rich agent-based model. *Ecological Modelling*, 221, 245-255.
- VAN ROSSUM, G. & DRAKE, F. L., JR. 1995. *Python reference manual*, Centrum voor Wiskunde en Informatica Amsterdam.
- WELFARE), E. A. P. E. P. O. A. H. A. 2016. Scientific opinion on assessing the health status of managed honeybee colonies (HEALTHY-B): a toolbox to facilitate harmonised data collection. *EFSA Journal*, 14, 241.