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Modelling of floral resources for the ApisRAM model

Deliverable D3.3

31 August 2021

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B-GOOD
Giving Beekeeping Guidance by cOmputatiOnal-assisted Decision making

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Preface

This Deliverable (D3.3) focuses on the development of the phenology models of floral resources (floral resource models) for bees, and is a major output of subtask 3.2.2. These 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 the ApisRAM (honey-bee colony) model being developed under the ALMaSS modelling platform within the WP5. The floral resource models will be validated in subtask 3.3.3 in Portugal, Belgium and the United Kingdom using ALMaSS testing landscapes developed in subtask 3.3.1. The Deliverable D3.3 thus describes the first version of the floral resource models which will be refined after the validation process is finalized. The floral resource models can be considered 'living' models and are designed in such a way that they can be easily updated when more/additional data on pollen, nectar or sugar production, phenology of bee-friendly species or plant species composition in landscape elements / habitat units important for bees, are made available. It is the intention that any new data be added to the database during and also after the project finishes.

The end product of the Deliverable D3.3 are text files describing production of pollen, nectar and sugar as a function of growing degree-days(GDD) (i.e., degree days above the base temperature T_b being a temperature threshold below which plant development stops) in various landscape elements / habitat units and crops important to bees across Europe. This Deliverable consist of the following components:

1) Report, being the present document, where the methodology and summary of outputs are described;
2) Appendix A: Database summarizing floral phenology models of important bee-friendly species [*Floral_phenology_models.xlsx*];
3) Appendix B: Database summarizing production of floral resources by important bee-friendly species [*Resources_production_flower_per_day.xlsx*]; and
4) Appendix C: Database describing composition of bee-friendly species in different EUNIS habitat types together with habitat-specific flower density [*Habitat_specific_flowering_density.xlsx*].

Appendices A, B and C are 'living' documents, thus their most up-to-date versions are stored in a GitLab repository (https://gitlab.com/ALMaSS/floral_resource_models) as open data under the CC-BY-NC license.

In addition, we developed the following open source scripts which together with all necessary input files are stored in the same GitLab repository (https://gitlab.com/ALMaSS/floral_resource_models) as open data under the CC-BY-NC license:

5) Scripts in Python (with necessary input files) allowing to relate plant phenology to growing degree-days [*GDD_calculation_wild_species_permanent_crops.py* and *GDD_calculation_annual_crops.py*]; and
6) Interactive script in Python for Jupyter Notebook (with necessary input files) allowing to calculate floral resources available for bees in different habitat units in different years and locations, and generating outputs for the ApisRAM model [*Resources_calculator.ipynb*].

To contextualise the Deliverable described here, the integration of Task 3.2 within the entire WP3 strategy and in relation to WP5 is first explained in section 1. The methods applied for this Deliverable are then presented and described in the Methodology section (section 2).

Summary

The main objective of WP3 is to develop a dynamic landscape model across the EU capturing the major floral resources for bees (flower resource model) considered a key driver of bee health status. To achieve this major goal, in task 3.1 the main landscape elements / habitat units important for bees across Europe were identified and classified in terms of plant composition. We used this information in subtask 3.2.2 to: (1) select bee-friendly species for which floral resource models were generated, and (2) up-scale the floral resource models for individual plants to landscape elements / habitat units. As the floral resource models need to be dynamic across the EU, the floral phenology of selected bee-friendly species was analysed in relation to growing degree-days. Pollen, nectar, and sugar production per flower per day, and habitat-specific density of flowers per unit area at the peak of flowering were assessed based on the database on nectar and pollen production (Deliverable D3.2), being the main output of subtask 3.2.1. These data were then integrated 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. Furthermore, WP3 and WP5 developed a methodology, including structure of output files, needed to incorporate floral resource models into the ApisRAM (honey-bee colony) model being developed under the Animal, Landscape and Man Simulation System (ALMaSS), as a part of its landscape component. The process of implementation of floral resource models into ALMaSS will be described in detail in Deliverable D5.1 (coming at Month n°28).

1. Introduction

WP3 “Ecology and environmental drivers” aims to develop a dynamic landscape model, capturing the major floral resources for bees, and to construct landscape suitability maps for honey bees across Europe. To achieve these general aims, this WP is divided into four tasks, with different sub-tasks, that have specific aims and links between them, as represented in the WP workflow (Figure 1).

In task 3.1, based on literature information, databases on plant traits and plant-pollinator interactions, beekeeper plant catalogues and bee expert advice (via a questionnaire sent to all B-GOOD members), the most important bee-friendly species in different landscape elements / habitat units across the EU were identified. The list of the bee-friendly species, together with the map and database of the major landscape elements at EU level (Deliverable D3.1), serve as input for task 3.2, and as a platform to construct the landscape suitability maps in sub-task 3.4.2.

The primary aim of the task 3.2 was the construction of the phenology models for the most relevant bee-friendly species across Europe. To complete this task, we first generated a database of the floral resources (Deliverable D3.2), including bee-friendly species, considering both crops and wild plants. For each plant species, information on the amount of pollen, nectar and sugar produced, number of flowers per unit area, single flower lifetime, and flowering start, peak and end dates were all compiled. The databases of major landscape elements with bee-friendly species (Deliverable D3.1) and of flower resources (Deliverable D3.2) were used in sub-task 3.2.2 to develop the floral resource models that will be incorporated within the ALMaSS modelling framework to serve the ApisRAM model (WP5), and other pollinator (mason bee and bumblebee) models being currently under development in other projects. The implementation of floral resource models in ALMaSS and their first-stage integration with ApisRAM are done for UK and Belgium (Deliverable D5.1 coming at Month n°28).

The plant species composition of each landscape element / habitat unit and the phenology models are derived both from estimations from phytosociological associations and from the literature, respectively. Validation is needed to assess the veracity of the values predicted from the models. The validation of the plant communities and phenology models (task 3.3) is being performed in three selected countries (Portugal, Belgium and United Kingdom) following specific field protocols developed by the WP3 team. The field protocols developed for this purpose will be integrated in the Deliverable D3.4 “Model validation and sensitivity analysis of phenology of floral resource model” (coming at Month n°36). Furthermore, task 3.3 also includes the construction of spatio-temporal dynamic landscape models for study areas in Portugal, Belgium and the United Kingdom, and the assessment and quantification of the floral resources in those study areas, that will be incorporated into the ALMaSS platform. The validated floral resource models will be updated within the ALMaSS platform to run together with the ApisRAM model (second-stage integration; subtask 3.4.1).

In the sub-task 3.4.2, the main goal is to build landscape suitability maps using geospatial data sources at the pan-European scale, namely land cover maps (from task 3.1), plant species distribution, weather data, digital elevation models and topographic data, and remote sensing to construct detailed spatio-temporal dynamic landscapes maps at the EU scale.

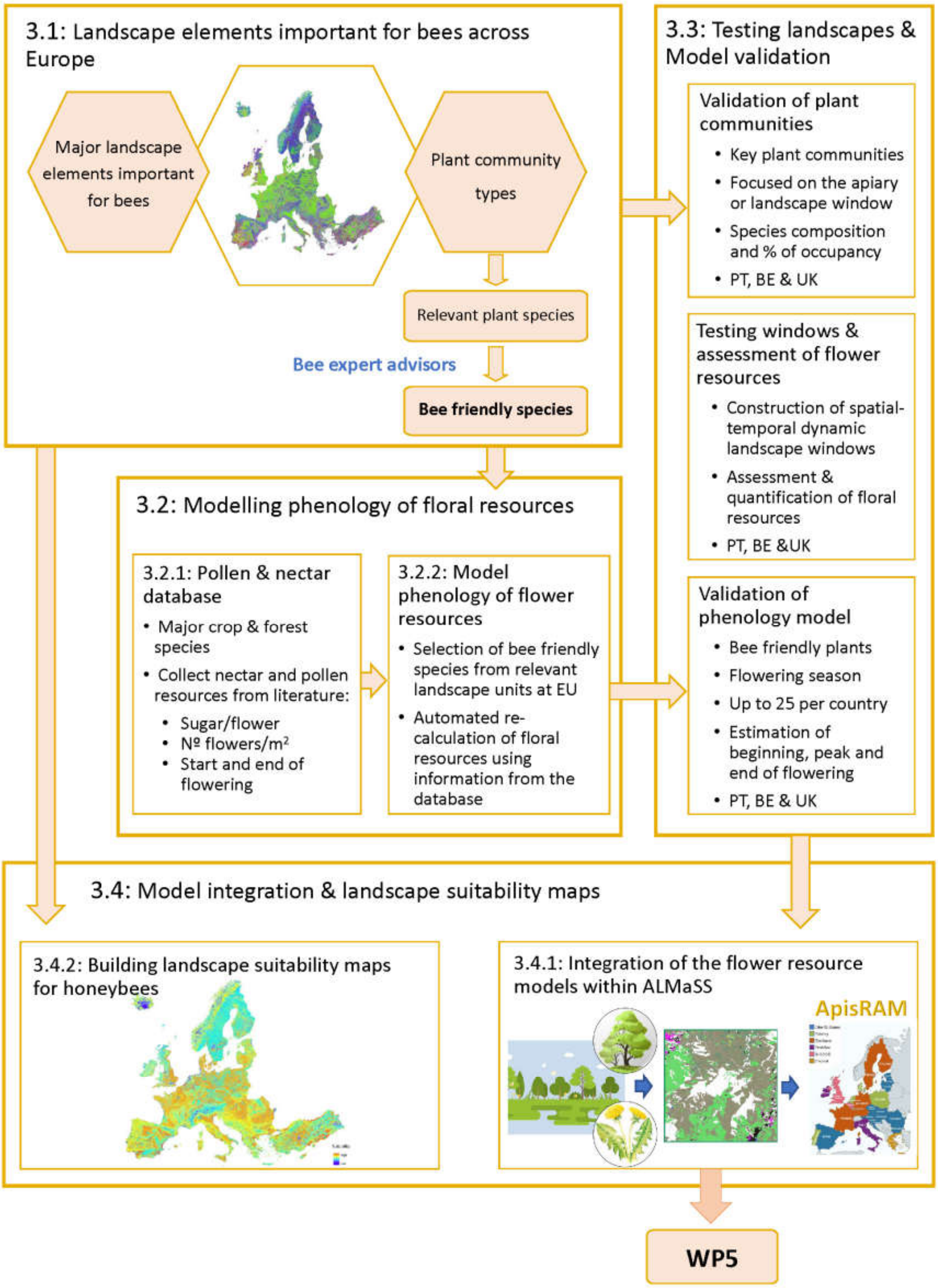


Figure 1: Diagram of the workflow of the work package 3, showing the major links between tasks and sub-tasks

2. Methodology

This section describes the methodology used to generate floral resource models for different landscape elements / habitat units and crops important to bees.

2.1. Datasources used to generate floral resource models

2.1.1. Database on nectar and pollen production

To be able to predict the quantity and quality of resources (pollen, nectar and sugar) available for honeybees in different habitat units over time, it was necessary to collect detailed qualitative data on pollen, nectar and sugar production, and floral phenology for plants across the EU. We were interested in both (1) nectar, providing adult bees with the energy required to perform their daily tasks, and (2) pollen, which is one of the food sources fed directly to larvae (juvenile stage) which is however also consumed in large amounts by adult worker bees, converted into jelly (brood food, royal jelly) in their hypopharangeal glands and then fed directly to larvae, which they need to grow and look after. In addition, sugar production was reported, as the amount of sugar that bees can extract from flowers (calculated via sugar concentration) traditionally serves as a proxy for nectar quality (Roulston & Goodell, 2011; Vaudo et al., 2015).

The data on pollen, nectar, sugar production and plant phenology (timing and duration of flowering, number of plants and flowers per unit area and information on flower longevity) were compiled in the database (Deliverable D3.2) as a main output of the subtask 3.2.1. The database, which is a ‘living’ document, currently contains information on 1612 plant species, belonging to 755 genera and 133 families. For crops and some trees (being important source of pollen) for which some information on production of resources was missing in the database (such as mass of pollen grain needed for calculation of pollen production in mg), additional targeted literature search was performed.

2.1.2. Databases on floral phenology for wild and crop species

For many species the information on floral phenology (day of year of start, peak and end of flowering season for a given year and location) was already collected for the database on nectar and pollen production (Deliverable D3.2). However, to better fit the phenology curves, additional data on floral phenology was collected and integrated to form a database.

The following datasources are currently included in the database on floral phenology:

- Pan European Phenology Database (PEP725): http://www.pep725.eu/ (Templ et al., 2018) including observations collected until 2016. 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.
  The majority of data provided by PEP725 is for wild plant species, but some observations are also available for crops, such as oilseed rape (*Brassica napus*), turnip rape (*Brassica rapa*), or alfalfa (*Medicago sativa*).
  This data is referred to as 'PEP'-data and tables containing this data are named with the prefix 'PEP'.

- Phenological observations collected by the Deutscher Wetterdienst (German meteorological service, DWD) from 1951 up 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 a 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 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.
DWD provides information for many wild plant species, annual crops (including data on start of flowering of sunflower, corn, potato, green bean, green pea and tomato, and data on peak of flowering of corn), fruit crops (including data on start, peak and end of flowering of apple, pear, cherry, morello, and plum; and data on start of flowering of apricot, peach, and different kinds of berries), and vine (including data on start, peak and end of flowering of early, middle-late and late ripeness).
This data is referred to as 'DWD'-data and tables containing this data are named with the prefix 'DWD'.

- The database on nectar and pollen production (Deliverable 3.2).
  This data is referred to as 'UJ'-data and tables containing this data are named with the prefix 'UJ'.

- 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.
  This data is referred to as 'COBORU'-data and tables containing this data are named with the prefix 'COBORU'.

For each observation of flowering of wild and cultivated, permanent plants (i.e., fruit plantations, vine, olives), the following information is collected in the database:

- ALT – altitude of the measurement location,
- LON & LAT – longitude and latitude (in decimal degrees) of the measurement location,
- PLANT_NO – code of the plant (according to *plantlookup.xlsx* file available at GitLab),
- BBCH – stage of plant development according to the BBCH-scale (60 – start of flowering, 65 – peak of flowering, 69 – end of flowering),
- DOY – day of year when a given plant development stage was measured,
- YEAR – measurement year.

For annual crops, in addition to those mentioned above, information on sowing is also provided:

- SDOY – day of year of sowing,
- SYEAR – year of sowing (if SYEAR=YEAR then we have a spring sown crop, else it is a winter sown crop).

The data collected were divided to form three databases:

- Database of floral phenology for wild species: *Database_floral_phanology_wild_species.csv*, and
- Database of floral phenology for permanent crops: *Database_floral_phanology_wild_species_permanent_crops.csv*, and
- Database of floral phenology for annual crops: *Database_floral_phanology_annual_crops.csv*.

2.1.3. Meteorological data

To be able to predict flowering in different locations and local conditions, flowering observations from 2.1.2 were related to meteorological data. For that purpose, we used the E-OBS dataset providing daily gridded land-only meteorological data for Europe from 1950 to present derived from in-situ observations. The dataset is available in two regular latitude-longitude grids: 0.1° x 0.1° and 0.25° x 0.25°, and contains the following meteorological variables: daily minimum, mean and maximum air temperature (in °C) measured near surface (usually at height of 2 meters), daily precipitation amount (total daily amount of rain, snow and hail in mm), daily mean air pressure at sea level (hPa) and solar radiation measured at the Earth's surface. The E-OBS data can be freely downloaded from the Climate Data Store of the Copernicus Climate Change Service (https://cds.climate.copernicus.eu/). For the generation of floral resource models we used E-OBS data in resolution of 0.1° x 0.1°.

2.1.4. Habitat units classification and composition

To be able to upscale the floral resource models from individual species to habitat units, the classification of habitat units important to bees across the EU together with plant composition is needed. Such habitat classification and typology together with plant species composition was provided for EUNIS Level 2 habitats as a main output of task 3.1 (Deliverable D3.3). Each plant species was further classified in terms of its bee-friendliness (BF Value varying from 0 to 11.5) considering its characteristics independent of the habitat. To evaluate the contribution of each plant species in terms of bee-friendliness within a particular habitat, the bee-friendliness index (BF Index) was generated as the multiplication of the BF Value by the species occurrence and by the average species cover within a given habitat. The BF Index therefore reflects the theoretical potential contribution in terms of bee-friendliness of a particular plant species within a particular habitat. The deliverable D3.3 provides details on methodology for BF Value and BF Index calculations.

Besides the database of major species that compose each landscape element type, and that are a relevant resource for honey bees, task 3.1 provided an updated map of habitat types (EUNIS level 2) generated based on the newest CORINE Land Cover 2018 database. This map will be used to assigned habitat unit types to landscape elements in the ALMaSS landscape models.

2.2. Generation of floral resource models for individual plants

2.2.1. Selection of bee-friendly species to be modelled

The database of relevant resources for honey bees (Deliverable D3.1) contains calculation of BF Value for 8029 species, 6333 out of them having BF Value > 0 meaning that they could be of potential interest for honey bees. As we were not able to generate the floral resource models for all these species, we decided to prioritize our efforts by first selecting plant species characterized by at least moderate habitat-specific bee-friendliness, i.e., with BF Index ≥ 20 within each of the EUNIS Level 2 habitats considered as important to bees. Such selection resulted in 314 plant species. These species were then analysed one by one starting from those with the highest BF Value.

In addition, we selected the following annual and permanent crops to be modelled:

- Fruit crops: apple (*Malus domestica*), plum (*Prunus domestica*), and sweet cherry (*Prunus avium*); strawberry (*Fragaria* ssp.);
- Vegetable crops: field / broad bean (*Vicia faba*);
- Edible oil and proteinaceous crops: oilseed rape (*Brassica napus*), turnip rape (*Brassica rapa*), sunflower (*Helianthus annuus*), olive (*Olea europaea*);
- Cereal crops: corn (*Zea mays*).

These plants were mentioned as being commonly visited by honey bees (Klein et al. 2007), with olives (Giovanetti 2018) and corn (Danner et al. 2014) being specifically a source of pollen. In addition, management plans (describing farm activities related to soil cultivation, and application of fertilizers and pesticides, as well as time windows and probabilities of carrying out these activities) for above mentioned crops already exist within the ALMaSS or are planned to be added in the nearest future.

2.2.2. Floral phenology modelling

Plant phenology is determined by endogenous genetic components of the species as well as various environmental factors, such as day length, temperature, water availability or soil properties (Cho et al., 2017; Zhao et al., 2013). However, intra-seasonal timing of plant phenological events is primarily driven by temperature and photoperiod. Ambient temperature influences flowering time by affecting the rate of growth and development throughout the plant life cycle, with flowering starting earlier in response to warmer temperatures. Some plants flower as day length increases in late spring (long-day plants), some flower as day length wanes as autumn begins (short-day plants), and some plants flower at certain times regardless of the photoperiods (day-neutral plants)

In the first version of floral resource models, the timing of flowering was related only to temperature. The impact of photoperiod / latitude on flowering will be tested for selected species for which floral phenology observations are reach enough. The results will be included in the updated version of the floral resource models. This will not require essential changes in the implementation for ApisRAM, as ALMaSS already provides daily information on sunrise and sunset for the location being modelled (based on the geographical coordinates of the location). Thus, the photoperiod can be directly calculated in ALMaSS and used to modify floral phenology if needed.

At the moment, we assume that each plant developmental stage, including flowering, has its own total heat requirement, and that the development can be estimated by accumulating GDD throughout the season. For calculation of daily GDD we used the following formula:

Daily GDD (°C) = ((Daily Max T °C + Daily Min T °C)/2) – T_b °C

For each plant selected in 2.2.1, we attempted to calculate the accumulated GDD needed for the flowering to start, to peak and to end. For all wild plant species, GDD were accumulated starting from January 1st and using the base temperature of 4°C. This base temperature can be later on adapted to local conditions and habitat type if needed. For crops we used crop-specific base temperatures, determined from the literature (see Table 1). For permanent crops (i.e., fruits, olives), GDD were accumulated starting from January 1st while for annual crops - from the sowing date.

Table 1. Base temperatures for crop species to be modelled

Crop	Base temperature T_b [°C]	Reference
Strawberry	3	Døving and Måge 2001
Field / broad bean	0	Stützel 1995, Boote et al. 2002
Oilseed rape	3 - 4	Andreucci et al. 2012, Böttcher et al. 2016
Turnip rape		
Sunflower	7 - 8	Robinson 1971, Sadras & Hali 1988
Corn	6	Sánchez et al. 2013
Apple	2 - 4	

Plum		Kalvāne et al. 2021, Woznicki et al. 2019
Sweet cherry		
Olive	9	De Melo-Abreu et al. 2004

For a given bee-friendly plant, we first selected all observations from the database on floral phenology indicating the flowering start, for each of them we calculated the accumulated GDD, and the mean and standard deviation from all these observations were reported. The mean accumulated GDD from all observations of flowering start was then used as a threshold after which the flowering of a given bee-friendly plant begins. Next, all observations of flowering start, flowering peak and flowering end from the same year and location were selected to calculate the mean (and standard deviation) GDD needed to be accumulated after the flowering start to reach the flowering peak and flowering end, respectively.

As the GDD calculations needed to be done for many species and observations (different locations and years), we developed Python scripts [*GDD_calculation_based_on_E-OBS_data_wild_species_permanent_crops.py and GDD_calculation_based_on_E-OBS_data_annual_crops.py*] allowing for the automation of calculations. Two scripts were necessary, as for wild plant species and permanent crops, accumulated GDD were calculated from January 1st, while for annual crops - from the sowing date.
The input files to scripts consists of:

- Database on phenology of wild species and permanent crops or annual crops, respectively,
- The E-OBS data on minimum and maximum temperatures in 15-year chunks, and data on elevation.

The main output files from scripts consist of (below, please note that 'plant_no' stands for code of the plant according to *plantlookup.xlsx* file):

- *[plant_no].csv* text files in which row represents data for a given plant, columns are: mean of accumulated GDD to flowering start, mean of accumulated GDD to flowering peak, and mean of accumulated GDD to flowering end; -1 values means no data;
- *[plant_no]stat.csv* text files in which each row represents data for a given plant, columns are: mean of accumulated GDD to flowering start, sd of accumulated GDD to flowering start, mean of accumulated GDD from flowering start to peak, sd of accumulated GDD from flowering start to peak, mean of accumulated GDD from flowering start to end, of sd accumulated GDD from flowering start to end; -1 values means no data;
- *[plant_no]fullresult.csv* text files in which each row represents one floral phenology observation, columns are: observation parameters (ALT, LON, LAT, DAY, YEAR, BBCH, and additionally SDAY and SYEAR for annual crops), accumulated GDD calculated for different base temperatures from 0 to 10 and for selected base temperature (4°C in our case). For observations indicating flowering start, the accumulated GDD from January 1st (or sowing date for annual crops) are provided. For observations indicated flowering peak or end, the accumulated GDD from flowering start are provided, and for selected base temperature only (4°C in our case).

[plant_no].csv and *[plant_no]stat.csv* files were then merged for all analysed plant species (*Floral_phenology_models.xlsx*) and simplified (by removing all unnecessary columns, e.g., with additional text comments) to form input files (*floral_phenology_wild_species_permanent_crops.csv* and *floral_phenology_annual_crops.csv*) to *Resources_calculator.ipynb* script. No data was indicated as -1.

2.2.3. Pollen, nectar and sugar production from flower / inflorescence per day

Pollen, nectar and sugar production from flower / inflorescence of a given plant was assessed, in µg per day, based on the database on floral resources. We assumed (unless otherwise stated in the reference for a given record in the database on floral resources) that production of floral resources was measured at the peak of flowering.

For each analysed plant species, we provided min, max and 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 resources production observed in between years and locations was often greater than in-between different habitat types.

The following procedure, step by step, was applied for each plant species:

- First, at the species level, all necessary re-calculations of floral resources were applied to obtain measurements of production from flower / inflorescence, in µg per day. This means that:
    - If production of resources was provided from flower / inflorescence but not per day, it was divided by the mean flower longevity. If information on flower longevity was not available at the species level, the mean at the genus level, or if not available – at the family level, was used.
    - If the nectar production was available but not the sugar production (or vice versa), the re-calculation from nectar to sugar (or from sugar to nectar) was done using the mean sugar concentration. If information on sugar concentration was not available at the species level, the mean at the genus level, or if not available – at the family level, was used.
- If, after the re-calculations, at least two independent measurements of pollen, nectar and sugar production from flower / inflorescence in µg per day were available at the species level, min, max and mean production of floral resources was reported. Else, the production of floral resources was estimated at the genus level, or if not possible – at the family level, using the same procedure.
- In some situations, production of floral resources (especially for pollen) needed to be estimated from the yearly yield (provided in kg/ha) and recalculated directly to mg / day / m^2. This was done assuming that flower density (and therefore production of floral resources) varies according to a triangular function across the flowering season (Baude et al. 2016). Production of resources at the peak of flowering was then calculated as:

$$\textit{Production at peak} / m^2 / \textit{day} = 2 \times \textit{yearly yield} \times 100 / \textit{flowering length}$$

The information on production of pollen, nectar and sugar from flower per day (or as a yearly yield) was then summarized for all analysed plants in the *Resources_production_flower_per_day.xlsx* database. The database was further simplified (by removing all unnecessary columns, e.g., with additional text comments) to form input file (*Resources_production_flower_day.csv*) to *Resources_calculator.ipynb* script. No data was indicated as -1. In *Resources_production_flower_per_day.xlsx* file, we provided full information on number of measurements from which floral resources production was calculated for each plant analysed, as well as detailed comments on the accuracy (i.e., if production of floral resources was provided for the species or estimated at the genus or family level). Note that by number of measurements, we mean number of entries on floral resource production available in the database on floral resources (Deliverable D3.2). Each such entry represents data acquired for a given plant from one plant community in a given year, and in most cases it is a mean value from many field measurements.

2.2.4. Habitat-specific flowering density

Habitat-specific flowering density, defined as the number of flowers per m^2 of a given habitat type, was assessed for each analysed plant species based on the database on floral resources. We assumed (unless otherwise stated in the reference for a given record in the database on floral resources) that flowering density was measured at the peak of flowering, similar as production of floral resources.

The following procedure, step by step, was applied for each plant species:

- For each analysed plant species, we reported min, max and mean of habitat-specific flowering density measurements.
    - If measurements were not available for a given habitat type, min, max and mean values were reported from all natural communities.
    - If only measurements from field experiments were available, the min, max and mean values were further rescaled by the species average cover in a specific EUNIS habitat type.
    - For tree species, in most cases the floral density was calculated by multiplying the number of flowers per tree by the tree density in a specific habitat type.
- If no flower density measurements were available at the species level, min, max and mean habitat-specific flower density was estimated at the genus level. Besides for some tree species (i.e., species from the *Betula, Carpinus, Castanea, Fagus* and *Picea* genus), we have not estimated flower density using data for the whole plant family due to possible big differences in-between plants from different genus within one family.

The information on habitat-specific flower density was then summarized for all analysed plants (*Habitat_specific_flowering_density.xlsx*) and simplified (by removing all unnecessary columns, e.g., with additional text comments) to form input file (*Habitat_specific_flowering_density.csv*) to *Resources_calculator.ipynb* script. No data was indicated as -1. Lack of measurements on resources production from flower per day and the need to use estimates from yearly yield was indicated as -2. In *Habitat_specific_flowering_density.xlsx* file, we provided full information on the number of measurements and habitat types from which habitat-specific floral density was calculated for each analysed plant, as well as detailed comments on the accuracy (i.e., if floral density was provided for the species or estimated at the genus or family level). Note, that by number of measurements we mean number of entries on flower density available in the database on floral resources (Deliverable D3.2). Each such entry represents data acquired for a given plant from one plant community in a given year, and in most cases it is a mean value from many field measurements.

2.2.5. Pollen, nectar and sugar production from habitat unit area per day

Production of floral resources from habitat unit area per day (i.e., pollen, nectar and sugar production per m^2 of a given habitat per day) at the peak of flowering were calculated by multiplying the production from flower per day by the habitat-specific flower density. If that was not possible due to lack of data on production from flower per day, the production from habitat unit area per day was recalculated directly from the yearly yield as described in subchapter 2.2.3.

The calculations of floral resources production from habitat unit area per day are done within the *Resources_calculator.ipynb* script.

2.3. Up-scaling of floral resources to habitat units

We assumed that flower density of a given plant species and thus production of floral resources varies with time according to a triangular function across the flowering season (Baude et al. 2016). This means that at the start of flowering the production is 0 and then it linearly increases to reach the maximum at the flowering peak, and then linearly decreases to 0 at the end of flowering. To produce the individual curves, first the information on mean accumulated GDD to flowering start, flowering peak, and flowering end was combined with production of floral resources from habitat unit area per day at the peak of flowering. If information on accumulated GDD to flowering peak was not provided in the *floral_phenology_wild_species_permanent_crops.csv / floral_phenology_annual_crops.csv* files (see subchapter 2.2.2), we assumed that it occurs in the middle of flowering period. If the flowering end was not provided, it was recalculated from the flowering peak assuming the peak occurs in the middle of flowering period. If flowering peak and flowering end were both not provided in the database on floral phenology, an additional search of literature regarding flowering length was performed, and estimates were based on the information found. If no information on floral phenology was provided, it was not possible to generate the floral resource model for this species.

The floral resource models for individual plants were then up-scaled to habitat units by superimposing curves according to species composition for a given habitat, i.e., summarizing production of species from a given habitat per degree-day. For such an upscaling to be possible, all species from a given habitat have to have the same base temperature that was used for the degree days calculations (in our case we assumed that this is 4°C, see subchapter 2.2.2).

Generation of floral resource models (curves) for individual plant species and the upscaling to habitat units is done in *Resources_calculator.ipynb* script. The script is available in the GitLab repository (https://gitlab.com/ALMaSS/floral_resource_models).

The script is organized in the following way:

i. The user needs to specify the location. The location is used to select location-specific meteorological data for the calculation of accumulated degree days to flowering start, peak and end. The user can either enter the specific latitude and longitude in decimal degrees or select the location by dragging their pointer on the map:

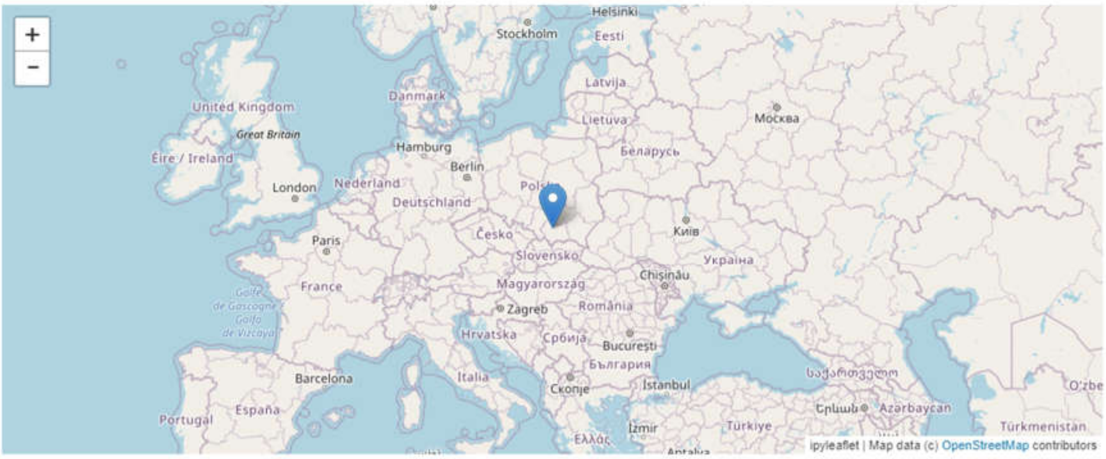
PLEASE SPECIFY THE LOCATION

Provide coordinates in decimal degrees:

LAT: 50

LAT: 20

...or drag a pointer on the map below




```
LATITUDE:  50.0
LONGITUDE :  20.0
```

ii. The user needs to specify the habitat type for which floral resource models will be calculated. The production of resources will be provided per 1m^2 of such habitat.

PLEASE SELECT YOUR HABITAT(S)

use 'ctrl' or 'shift' for multiple selection

HABITATS
- D3 - Aapa, palsa and polygon mi
- D4 - Base-rich fens and calcareo
- D5 - Sedge and reedbeds, norma
- E1 - Dry grasslands

Please provide coverage in % for each of the selected habitats and confirm with 'enter'

```
Enter percentage of E1 - Dry grasslands:
habitats chosen :  ('E1 - Dry grasslands',)
100% available
```

It is possible to select more than one habitat type but the percentage of each habitat type needs to specified separately.

iii. After the selection of habitat type(s), the floral resource models are generated for individual plant species and scaled-up to floral resource models for selected habitat type(s). In addition, output files for ALMaSS are generated.

iv. The last part of the script allows the generation of floral resource models for selected years, the calculation of the yearly production of resources and the averaged production (curves) for selected years is then displayed. The user can specify any years between 1950 and 2020:

PLEASE CHOOSE YEAR(S) FOR SIMULATION

Years: 2010 – 2020

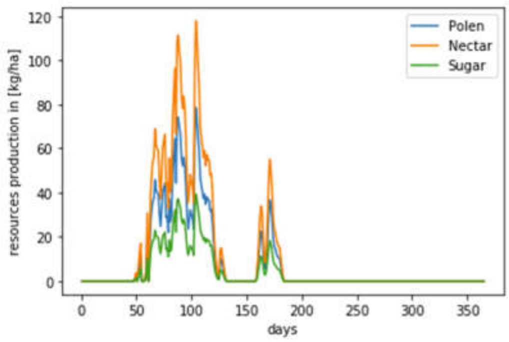
```
Processing weather data for years  [2010, 2011, 2012, 2013, 2014, 2015, 2016, 2017, 2018, 2019]
```

RUNNING SIMULATION...

```
year 2010 , 252 days above 4 deg C , total pollen production was 2743.1598904669077 kg/ha
year 2011 , 250 days above 4 deg C , total pollen production was 3098.8062517404637 kg/ha
year 2012 , 260 days above 4 deg C , total pollen production was 2758.5256892230573 kg/ha
year 2013 , 234 days above 4 deg C , total pollen production was 2204.1488907453822 kg/ha
year 2014 , 284 days above 4 deg C , total pollen production was 3467.0923373247933 kg/ha
year 2015 , 277 days above 4 deg C , total pollen production was 2893.037617191126 kg/ha
year 2016 , 273 days above 4 deg C , total pollen production was 3277.851689408707 kg/ha
year 2017 , 265 days above 4 deg C , total pollen production was 3379.310382437577 kg/ha
year 2018 , 255 days above 4 deg C , total pollen production was 2371.460804789752 kg/ha
year 2019 , 289 days above 4 deg C , total pollen production was 3148.7150979300095 kg/ha
```

RESULTS

```
average production for years (2010, 2020) :
```



2.4. Outputs for ALMaSS – an overview

For each habitat and crop type, the data input to ALMaSS is comprised of the x,y pairs from the floral resource model indicating the inflection points describing the amount of pollen, nectar and sugar per day, available as a function of the number of GDD experienced above a threshold temperature (e.g., Fig. 2). On reading the curve into ALMaSS the gradient between two inflection points is used to calculate the amount of resource added/subtracted per day based on the GDD experienced. This model is driven using the standard ALMaSS weather data based on average daily temperature. This, together with defining the type of floral resource model for each element in the landscape map, allows to track the dynamics in floral resources available to bees in different regions and under different weather patterns.

The process of implementation of floral resource models into ALMaSS will be described in details in Deliverable D5.1 (coming at Month n°28).

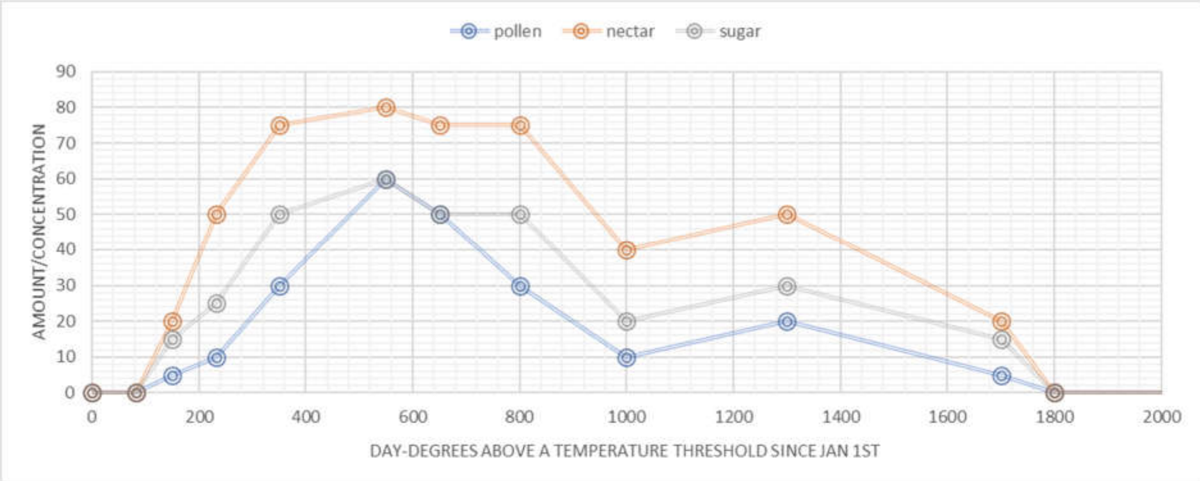


Figure 2. Nectar, pollen and sugar production (y-axis) against day degrees above a threshold (x-axis). This is the basic data used to create the nectar and pollen curves.

2.5. Important remarks

The floral resource models are presently generated using habitat compositions from Deliverable D3.1. These compositions do not take into account differences occurring in different pedo-climatic zones. Instead, it represents the 'average' European situation. This has important consequences for the floral resource models, mostly resulting in overestimation of resources as species from different pedo-climatic zones are combined together in one habitat type (e.g., different species of *Quercus* occurring together in broadleaved deciduous woodland (G1 EUNIS habitat type). This will be overcome in the second version of the models (coming later this year), in which specific compositions will be provided for each of the pedo-climatic zone in Europe. This, however, will not influence the methodology described in this report. Our flexible approach allows to modify habitat composition according to local conditions and easily re-run the *Resources_calculator.ipynb* script to generate necessary outputs for ALMaSS.

3. List of appendices

Appendix A: *Floral_phenology_models.xlsx*
Appendix B: *Resources_production_flower_per_day.xlsx*
Appendix C: *Habitat_specific_flowering_density.xlsx*

Appendices are 'living' documents, thus their most up-to-date versions are available in the GitLab repository (https://gitlab.com/ALMaSS/floral_resource_models) together with all scripts and necessary input files needed to generate floral resource models.

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