Floral resource quantification and imbalance in food supply and bees' predicted presence in the Netherlands

A GIS based study of pollen and nectar availability for the conservation of pollinators

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Abstract

The number of pollinator species in the Netherlands is declining, critically pressuring systems depending on their pollination function in the ecosystem. This includes ensuring the pollination of most of the grown crops for food supply to human populations. Additionally, society faces the threat of bee diversity loss in the Netherlands, and worldwide. This research entails the spatial quantification of pollen and nectar in the Netherlands over the months in 2022. It encompasses different methods of quantification, from measuring an attractiveness proxy based on predicted presence (SDMs) to attributing production values based on the plant communities present in different land uses and the classification of urban areas into different land uses. It yields into monthly distributions and a yearly average nectar production map which was compared to bee diversity distribution. This allowed to identify areas imbalanced in food supply and demand that require extra attention. These results can then be handed to decision makers for development of better management practices regarding social, technical, or governmental implementations. It could ensure an increase in the amounts of pollen and nectar and further help the conservation of critical species. The findings are that the natural areas are the only ones with a matching high bee diversity and high nectar production. The production in itself is evenly distributed geographically. Over the months, the production of both pollen and nectar reaches a peak in spring while nectar production has a second peak in autumn. On average, the methods yield into different peaks of production for nectar, either May or September. This study lays as a foundation for future research through the identification of missing information in literature. It creates a methodological pathway and highlights what could be obtained from a similar research with more data available.

Contents

Glossary

The following section presents a glossary of key concepts used throughout this study. It is intended to provide readers with a clear understanding of the terminology used and to facilitate comprehension of the main ideas presented in the thesis. The glossary contains definitions of important terms and concepts used in the main text and is organised alphabetically for easy reference. This section serves as a helpful resource for readers who may not be familiar with the technical terminology used in this study and clarifies the meaning of the terms used in this study.

Biodiversity

Biodiversity is defined by the Convention on Biological Diversity (CBD) as "*the variability among living organisms from all sources including, inter alia, terrestrial, marine and other aquatic ecosystems and the ecological complexes of which they are part*" (CBD, 2006). Different levels of diversity can assess biodiversity, including genotypic expression within a species, to species richness. The highest level is that of the ecosystem, where biodiversity is assessed through the functioning of the ecosystem. This study focuses on the conservation of biodiversity in the Netherlands in the sense of the diversity at species level, since it is a study towards conservation of pollinator species.

Geographic Information System

Geographic Information Systems (GIS) are 'spatial systems that create, manage, analyse and map all types of data' (ESRI, 2022). It is a software system for processing and analysing data, with the emphasis on combining and displaying the geographical component of this data. A powerful tool for decision making, communication and efficient problem management, it has grown significantly over the last decade and is now used daily by almost everyone (e.g. GPS applications or satellites data).

Plant community

A plant community is a group of plant species that coexist and interact within a particular habitat or ecological setting. It is a dynamic, interconnected collection of plants that exhibit similar ecological characteristics and often share common environmental requirements. Plant communities allow us to assess the collective abundance, diversity, and distribution of plant species that contribute to the availability of nectar and pollen for pollinators. It is also known as plant sociological nomenclature in the scientific community.

Pollinators and Pollination

Pollination is the process of transporting pollen from the male stigma of a flower to the female stigma. As plants are not able to move *per se*, their reproduction depends on other agents such as 'pollinators', species that ensure this transport by attaching pollen grains to their bodies when they collect pollen and nectar from flowers and feed on it. In the Netherlands, these include a wide range of bee species, as well as various insects such as bumblebees and hoverflies species among others.

Raster map

A raster map is a type of digital map that represents geographical data in the form of a grid of pixels. Each pixel contains a value that corresponds to a particular location on the Earth's surface. Raster maps are commonly used to represent continuous data such as elevation, temperature, and land cover. They can be created from a variety of sources, including satellite imagery, aerial photography, and digital elevation models. Raster maps are often used in GIS and remote sensing applications to analyse and visualise spatial data.

Species Distribution Modelling

Species Distribution Modelling (SDM) is a GIS method used to establish spatial relationships between species and habitat requirements applied in ecological studies. It combines several layers of data relating to the conditions of a specific environment (e.g. rainfall data, land use, soil type in the Netherlands) to bring together the areas that meet all the life requirements of a species. It therefore creates a prediction of the area where a specific species might be observed which differs -and care should be taken when using SDM maps- from the area where it will be observed.

1.Introduction

1.1 Pollinators decline

Global populations of wild bees and other pollinators are decreasing in number and diversity while conversely, global populations of managed bees (hereafter referred to as honey bees) are increasing (IPBES, 2016). The dynamics differ worldwide, with honey bees declining in Europe and North America (Biesmeijer et al., 2006), but the total number of pollinator species is decreasing worldwide, and even more rapidly in Europe and North America. In the Netherlands, over the last few decades, the number of pollinator species has decreased by about 30% (Biesmeijer et al., 2006) and 55% of the 355 Dutch species are listed as endangered in the red list (Reemer et al., 2018). 35 of those 355 -about 10%- are already declared extinct (Schuiling, 2013).

The key driver of such decline is said to be the decline of preferred host plant species (Scheper, 2014). The development of the current intensified agricultural system, aiming for high yields through pesticides and mono-agricultural fields, leads to many species losing their preferred foraging plants, nesting areas (Biesmeijer et al., 2006; Schuiling, 2013) and in general food resource availability. This is due to multiple anthropogenic pressures such as intensive agriculture, climate change or spread of diseases (Vanbergen, 2013). Moreover, the use of Genetically Modified Organisms (GMOs) for more fitting crops includes herbicide tolerance and insect resistance for which the impact on pollinators is still unknown but might cause further issues (IPBES, 2016).

The decline of wild pollinators populations is all the more critical as it appears that honey bees are only responsible for a minor part of the pollination process. Breeze et al. (2011) assessed that about 30% of crop-pollination services were ensured by honey bees in the UK, with the remainder being provided by wild pollinators.

1.2 Valuation of pollinator services

The high value of pollinators to the economy, due to our heavy reliance on pollination for growing crops and maintaining high yields, shows how essential these species are to food supply security. Wild bees, hoverflies and butterflies pollinate up to 90% of wild plants, and most cultivated crops (van Rooij et al., 2020). Additionally, pollinators increase the production of 70% of the crop species directly used for human consumption which accounts for 35% in volumes (Klein et al., 2007). In Europe, 84% of the crop species cultivated directly depend on insect pollinators (Williams, 1994). The value of such service worldwide has been estimated by different studies and ranges from 153 billion euros (Gallai et al., 2009) to 577 billion dollars (IPBES, 2016) and in the Netherlands between 1.1 and 3.8 billion euros annually (Blacquière, 2010).

1.3 Land use change threat

Urbanisation and intensive agriculture have been (and will be) two of the main drivers of land-use change in recent decades. These changes endanger the quality of ecosystems and put pressure on the remaining species as globally, 80% of the crop pollination is ensured by 2% of the bee species which account for just over 5% in number of bees (Kleijn et al., 2015). As monocultures are inhabitable for pollinators due to low abundance and diversity of pollen and nectar, they turn to nature reserves, semi-natural areas or even to cities to survive (Ozinga et al., 2018). Indeed, the breadth of the nectar sources is a key to a positive response of pollinators to agricultural intensification (Wood & Roberts, 2017). Stakeholders of the food industry are increasingly acknowledging the importance of pollination and are therefore looking for ways to ensure pollination within large monocultural fields. This comes with a heavy increase of honey bee colonies worldwide in order to offset the increase in volume of pollination-dependent crops production, of about 300% over the last 50 years (IPBES, 2016) but even for honeybees that are known for being generalists (not specific on which plant to forage), monocultural fields make the colonies lack nutrients and it hampers colony growth (Bonoan, 2019). In comparison to intensive agricultural fields, urban areas therefore offer more diversity in food, less harmful environmental chemicals and enough and/or suitable nesting options. Wild bees are known to thrive in areas with moderate levels of urbanisation due to their low requirements for survival (Baldock, 2020; Hall et al., 2017). Urban areas often contain large parks and gardens that provide a rich environment suitable for bee habitats while serving the needs of the urban population, with a higher abundance and richness of non-native plants (Baldock et al., 2019). These moderate urbanisation areas contribute to conserve pollinators by providing high food availability (Tew et al., 2021) and nesting sites, provided that they are not transformed into denser urbanisation areas (Wenzel et al., 2020).

1.4 Climate change threat

Climate change will continue to impact ecosystems in the future, leading to changes that will require species to adapt. Different species will respond differently to these changes, which will alter the long-established mutual relationships found in various ecosystems. In the case of pollinators, climate change results in earlier plant flowering, causing the peak availability of pollen to be occur earlier in the year. This can pose a challenge for pollinators as it may coincide with their hibernation period. This phenological asynchrony might endanger reproduction for plants and cause food shortages for pollinators (Rafferty & Ives, 2012). While certain species may quickly adapt by ending hibernation earlier, most have been observed to instead migrate towards new locations with similar conditions to what they previously encountered. Literature is still unsure about the implications of such a mismatch, but it is likely that it causes risk for long-term security for plant and pollinator species (Fründ et al., 2013; Kudo & Cooper, 2019). This phenology asynchrony further increases the importance of monitoring the evolution of both food availability and demand from pollinators, and compare them.

1.5 Current studies focus

The decrease in pollinators' species richness has been observed, the major drivers of disturbances have been presented and their relation to food shortage has been demonstrated. However, little has been researched on food supply. Most of the studies regarding pollen and nectar deal with amounts of pesticides taken up by pollinators that can endanger them or humans. Aside from pesticides, most studies address allergies to pollen or ways to bring pollinators back to fields. These studies focus on different methods such as attention to the type of plants on e.g. the field margins that can allow for a significant difference in pollinators, such as bumblebees presence (Pywell et al., 2006). They also investigate ecological mowing: consciously mowing after the blooming of flowers e.g. in road verges (Stip & Dijkhuis, 2021). Finally, a recent implementation is a focus on 'bed and breakfast' spots among landscape elements (e.g. hedges with various blooming species) for creating pathways for pollinators to reach other niches (Ottburg & Lammertsma, 2022). Some studies focus on ways to quantify floral resources e.g. in temperate grasslands, but most often they use count variables as indirect proxies to pollen and nectar quantification (e.g. flower count or floral area). For temperate grasslands, out of 158 pollination studies, only one was using a direct measure of nectar values (Szigeti et al., 2016). This emphasises the struggles of obtaining clear data and methods available on nectar and pollen production of various plant species. On a more general level, Baude et al. (2016) quantified nectar sugar content in natural and agricultural areas in the UK while Tew et al. (2021) focused on urban areas. These two studies are based on field studies of hundreds of plants. Layek et al. (2022) also established that no model based study was found in the literature for pollen or nectar quantification. This is a major gap in research in such quantification both geographically (no study in the Netherlands) and methodologically (no model-based study).

1.6 Rationale

Investigating the distribution of pollen and nectar production in the Netherlands would allow to identify key areas where the lack of food could be a factor preventing pollinators to be present in that area. This information can be used to inform conservation efforts and management strategies aimed at promoting pollinator diversity in rural and urban areas to help pollinators thrive in such area. Such research can contribute to the conservation of endangered wild pollinator species by providing valuable information to guide conservation efforts, such as the creation of pollinator-friendly habitats and connections in the landscape as well as focus on specific areas for stronger reductions of pesticide use. This leads to contribution towards understanding where can which species be best helped with food resources to prevent their decline and ensure their vitality.

These conservation efforts fall in line with the National Bee Strategy and the Coalition of the Willing on Pollinators, which is a Dutch initiative bringing together 15 countries over taking action for pollinators. The National Bee Strategy aims at reaching 50% less species decreasing in population, 50% more species increasing its population by 2030, but also increasing the bee distribution and ensure efficient pollination (Ministerie van Landbouw, Natuur en Voedselkwaliteit, 2018).

In addition to conserving species, an essential component of sustainability is ensuring food security. It refers to the availability of and access to sufficient, safe, and nutritious food for all people (World bank, 1996). Wild pollinators are critical for ensuring human food security through their function of providing an important ecosystem service. As part of rethinking the current agricultural model, this is a step towards a more resilient food system that protects its own natural agents for ensuring efficient and sustainable systems in the crop cultivation, therefore looking at the issue in a systemic way.

The absence of endangered pollinators in agricultural fields (see *Section 1.3*) could be seen as against using ecosystem services as an argument for this research. However Kleijn et al. (2015) also specify that diversity increases the magnitude and stability of ecosystem functioning. Winfree et al. (2018) also established in the USA that maintaining the service provided by the ecosystem through crop pollination requires a certain regional scale bee diversity. Thus, working for the conservation of endangered species, whether directly involved in crop pollination or not, ensures the stability and resilience of an ecosystem which as a whole ensures food security. On a field level, endangered pollinators are not critical to crop pollination. However looking at the landscape level they ensure the good functioning of the ecosystem. They also ensure the pollination of non-crop plants, which contributes to the quality of nature, valuable in many ways to our society.

1.7 Research Question

The core concepts presented in the glossary, in relation with the problem and research gap established above lead to a focus on answering the following research question:

What was the quantitative distribution of floral resources for pollinators across the Netherlands during the year 2022, and how does this compare to the distribution of wild pollinator species?

In order to answer this research question, the following sub-research questions will be answered:

1. Which quantification methods can be used to reach the floral resource distribution and how do they compare?

2.How are floral resources (nectar and pollen) spatially distributed over the Netherlands per month of the year 2022? How do the different methods perform?

3.How does pollinators' richness compare to floral resources over the Netherlands in the year 2022?

2.Methodology

The following section outlines the methods used to answer the aforementioned research question. After an extensive review of the existing methods and literature, focus was directed towards the floral resource quantification side for time constraints. The methods involved the use of: (1) richness as a proxy to abundance of nectar and pollen production. (2) the location of plant communities to spatially calculate the resources. (3) land-use types classification to obtain a finer scale of the spatial distribution. (4) a more detailed urban land-use classification and the use of data from a British study. (5) the summing up of the results of methods 3 and 4. Finally, this last result has been compared with the distribution of bees richness in the Netherlands. The details of each method including data collection, data analysis procedures, and limitations are described in the following subsections.

2.1 General information

Previous work

This study builds on previous works of floral resource quantification or related topic. The Biodiversity & Society research group in Naturalis has carried out the development of SDM maps predicting the living areas of various plant and pollinator species in the Netherlands and wondered whether it could be used to make a prediction model to quantify the availability of food for pollinators over the months. Furthermore, students from the HAS hogeschool Den Bosch, as a partnership with Food4Bees, investigated the setting up of a database allowing to map the relative scoring of pollen and nectar depending on the type of areas as well as an interface to access it. This work allowed them to come up with a first distribution for rural areas through including crops, but it remained a relative scoring and has faced limitations regarding the assessment in urban areas. The second and third methods of floral resource quantification are inspired by this work.

Starting from this point, I had the opportunity with Naturalis and its contacts to speak to multiple researchers of this field or of related expertise to discuss my study and get access to datasets, get validation or get insights into assumptions I could make. The list of the experts I had a consultation meeting with is listed in *Appendix 3*. Building on these interviews, extended research was performed to analyse the available work regarding floral resource quantification. This research builds on all these insights and concentrates on quantifying pollen and nectar over the year, comparing it with predicted living areas of bee species to categorise key areas. The most time-intensive quantification method was turned into a GIS-based model for it to be easily reused with other data (data from another year, more precision in the data, or another geographic area).

Software details

The main analysis of this study was performed through ArcGIS Pro 2.9.5, one of the main GIS software developed by ESRI. This allowed to perform treatments, combine layers of data and create a reusable model with the ModelBuilder functionality. This model yields into maps which can be later used for interactions by users in order to gain insights. Some data was retrieved from the software SynBioSys in its 3.6.8 version. SynBioSys (for Syntaxonomic Biological System) is a software developed by WUR in order to make accessible biological data on different levels: species, plant communities or landscapes. Microsoft Excel was used for compiling plant communities data and the website ezgif.com was used to turn the monthly maps into animated GIFs. Python was also used through Jupyter Notebooks for making the bar charts.

Data sources

For clarity, the databases used and all the details necessary for reproduction of the analysis have been compiled in *Table 1*. More information regarding how each database was used is given later in the methodology section.

Table 1: Data sources and description of data used for the analysis of this thesis.

DATABASE	VERSION	RETRIEVAL DATE	DATA SOURCE
SDM maps	2020	28th March 2023	Naturalis
Bee species visiting plants	/	May 2023	WUR
Waarneming	/	May 2023	Waarneming
SynBioSys	v3.6.8	14th April 2023	WUR
FloRes	25/08/2022	11th April 2023	Data Dryad, Baden-Böhm et al., 2022.
TOP10NL	Compleet	18th April 2023	PDOK
DKK	v4	9th May 2023	ESRI_NL_Datasets, Arcgis Online
BAG 3D	April 2020	9th May 2023	ESRI_NL_Datasets, Arcgis Online
CBS BBG	BBG2017 v1	18th April 2023	PDOK
Groenkaart	15/04/2017	25th April 2023	Atlas Lee-fomgeving, RIVM
LGN	LGN2021	14th June 2023	LGN
BWK Karteringseenheden	/	14th June 2023	Revisie Vegetatie van Nederlands
Urban nectar production	/	April 2023	Tew et al., 2021.
Bijendiversiteit	2017	June 2023	Atlas Natuurlijk Kapitaal, RIVM
Naturalis land use map	/	May 2023	Naturalis

2.2 Floral resource quantification

2.2.1 Method 1: Richness map and attractiveness weighting.

The first method applied has been chosen through discussions with researchers in Naturalis. It is quantifying an indirect proxy to abundance through combining SDM maps of the most visited plant species and weighting based on the number of bee species foraging the plant. The overall workflow can be seen in *Figure 1.*

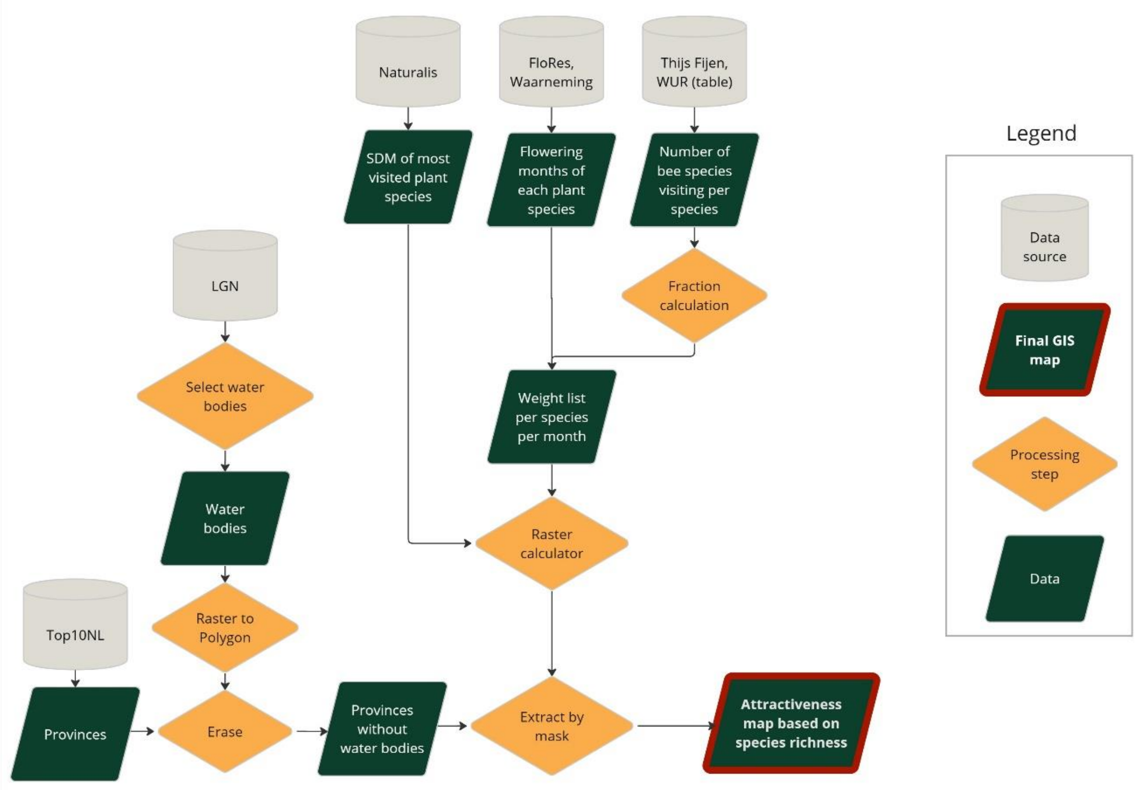

Figure 1: Workflow diagram of method 1: richness map and attractiveness weighting. The raster calculator step consists of summing up the weighted rasters as shown in Equation (1).

The multiple SDM maps provided by Naturalis deliver presence/absence maps for the desired plant species with a resolution of 100m x 100m. These maps of each target plant species were first weighted each using a fraction calculated from the number of bee species visiting the plant species. These values of the 50 plant species with the most bee species visiting observed were compiled by Fijen & Kleijn (n.d.) and are listed in *Appendix 1*. The weighting was then made as follows: the 50^{th} plant species was assigned a weight of one, while the weight of the others was determined based on the ratio of their number of bee species visiting compared to the one of the 50th plant species. As a result, the weights ranged between one and 4.46, reflecting their relative importance in terms of bee species interactions. These values and the presence/absence maps were then overlaid together with each flowering plant on a specific month to generate a map of plant species richness, which indicates the number of different plant species expected to be present in a given area, weighted by their number of bee species visiting. The flowering months used were taken from FloRes (Baden-Böhm et al., 2022) for the species that are present in it, and the others were derived from the observation data of Waarneming (n.d.). The species not present in both FloRes and Waarneming were not included in the calculation.

Mathematically, the calculation can be transformed into the following equation. This equation was used in raster calculator for the production of the maps:

$$A_{month} = \sum_{p\ month} R_p \cdot w_p \qquad \text{Equation (1)}$$

Where:

A_{month} is the total attractiveness value of a specific month, while p represents each plant species flowering for this particular month. R_p is the presence/absence raster map of the p plant species and w_p is the weight of species p. All these values are dimensionless.

This method was used for 44 of the 50 most attractive-to-bees plant species in order to reach the cover of the highest amount of species for which data was available. *Glechoma hederacea*, *Frangula alnus* and *Tussilago farfara* were not included because Naturalis did not have the SDM maps available. The three other are *Hieracium pilosella*, *Charmaenerion augstifolium* and *Rhamnus frangula*, for which no flowering month was found. The method was also performed with only the 36 species present both in this list of the 50 most attractive species as well as in the FloRes database (database used in the following methods, see *Sections 2.2.2 and 2.2.3*) from Baden-Böhm et al. (2022) in order to increase the comparability between methods. More information on this method is available in *Appendix 2.1*.

This method does not provide information on the quality or quantity of nectar produced by the plants. It is therefore not a quantification of floral resources, but provides insights into the repartition and has been assessed as an interesting proxy by some experts consulted (see *Appendix 3*). Indeed while not providing any production values (i.e. in mg/m²/day), this method allows to identify areas rich in plant species delivering resources for pollinators, thus communicating on their appeal for pollinators which in turn, allows to identify areas requiring a potential need for better management.

2.2.2 Method 2: Plant communities distribution.

In the second method of this study, the SynBioSys and FloRes databases were combined to analyse subsets of 36 and 29 plant species that are present in both databases, respectively for analyses of nectar and pollen. The overall workflow diagram utilised can be seen in *Figure 2*, and a more detailed workflow can be found in *Appendix 2.2*.

SynBioSys (2023) utilises data from the Dutch vegetation database (LVD) and various atlas books to gather information. One of these books is the *'Atlas van Plantengemeenschappen'* which, through the software, generates a comprehensive list of plant communities in the Netherlands. This list includes the plant species present in each community (with a probability) as well as their vegetation cover. By integrating this data, it becomes possible to obtain a raster map (resolution of 1km x 1km) showcasing the distribution of plant communities. This raster map induces the same resolution for the method's results. Additionally, a table providing details on the vegetation cover and faithfulness (probability of presence) of plant species within each plant community is generated. The software encompasses a total of 1544 species.

The FloRes database, developed by Johann Heinrich von Thünen-Institut combines studies available to provide a data list of the most important traits of plant species at peak flowering to work on floral resource quantification (Baden-Böhm et al., 2022). This includes the flowering period of the species, floral unit density (number of open flowers per square meter), as well as pollen and nectar content per open flower. These traits are mainly derived from field measurements studies, most of which happened in Europe (Baden-Böhm et al., 2022), with two sample sites. The combination of all these traits in a single database is said to be a novelty and no more extensive database has been found, hence the selection of this database.

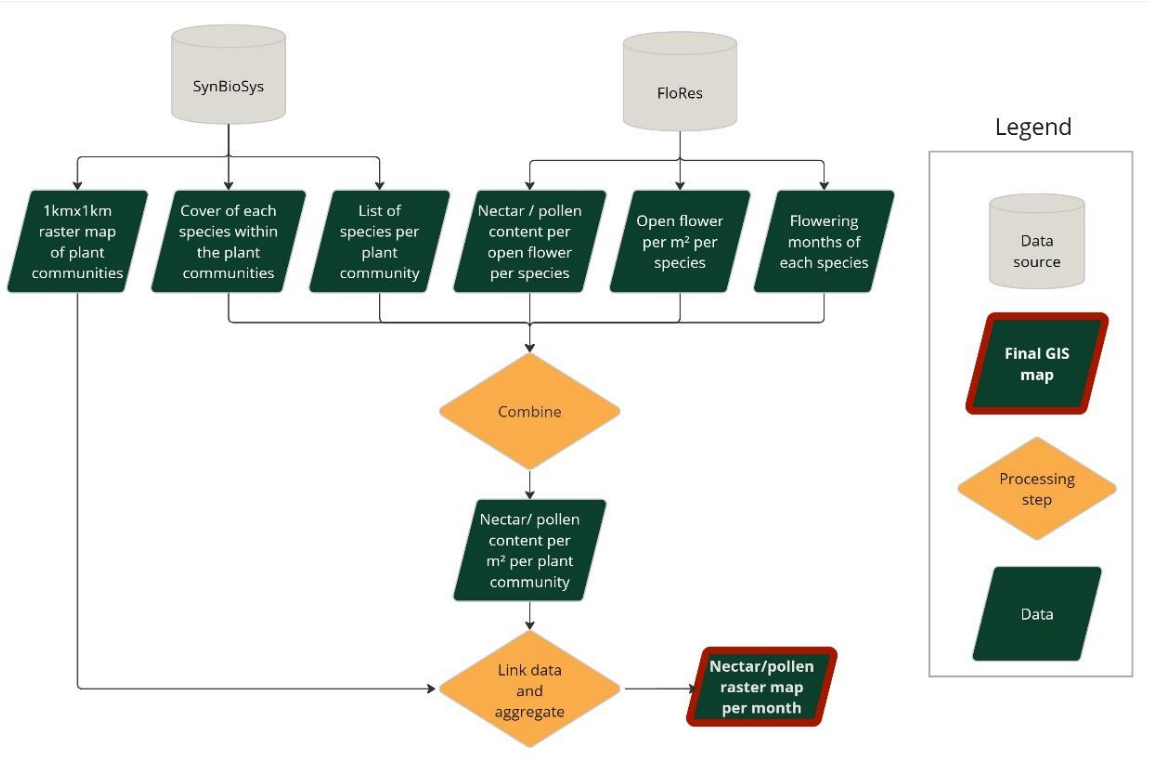

Figure 2: Worflow diagram of method 2: plant communities distribution. The combination consists of summing up the production value for all species flowering at each specific month of each plant community as explained in Equation (2).

FloRes lists all attributes for 72 species, creating a large imbalance compared to the 1500 species in SynBioSys. Out of these 72 species, 66 are also present in SynBioSys, and 29 of those are part of the 50 most attractive for bees (see *Section 2.2.1*) while 37 out of 50 are included when looking only at density and nectar sugar content. The analysis has therefore been performed with nectar sugar content, which allows to analyse 37 species for nectar (compared to 27 for nectar volume). However, the aggregation between the 50 most attractive plants and FloRes was slightly different. Two salix species (*Salix caprea* and *Salix repens*) were covered by FloRes through the same 'Salix spec'. For clarity, 37 plant species out of the 50 most attractive were considered and they are associated to 36 data rows of the FloRes database. Regarding pollen, only the 29 species that had data out of the 36 ones were included. The list of associations between FloRes and these species is in Supplementary data 2: Top50_to_FloRes_attribution.

The spatial distribution of plant species and their vegetation cover from SynBioSys were then linked to the floral traits to spatially quantify the distribution of pollen and nectar. The probability of the presence of a species within a plant community was utilised as a weighting factor to this.

Mathematically the calculation for the quantity of nectar over an area can be turned into the following equation:

$$n_{prod} = \sum_{species} vc \cdot f_{density} \cdot N_{flower} \cdot P \qquad \textit{Equation (2)}$$

Where:

n_{prod} is the nectar production density and is expressed in mg/m²/day. *vc* is the vegetation cover of the species in percentage. $f_{density}$ is the floral unit density, expressed in number of open flowers/m². N_{flower} is the nectar sugar content in mg per open flower of the species and P is the probability that this species is present in the plant community in percentage. The pollen value is derived with replacing N_{flower} by a similar pollen value.

This calculation was performed through a combination of Excel and ArcGIS Pro. Excel was used to link and multiply the probability and cover area of each plant species to yield into a single nectar and pollen value for each month of each plant community. When overlaying the data of the different plant communities, the maximal value was selected when multiple plant communities occurred in the same cell. ArcGIS pro was used to join this data to the distribution of the plant communities. After linking the data to each plant community, the polygon data of each plant community was turned into raster and the adequate data was selected for each plant community and each month (see *Appendix 2.2* for detailed explanations).

2.2.3 Method 3: Habitat classification.

This method is similar to the previous one in using SynBioSys and FloRes databases. However here, the study area was classified based on its land use type before being linked to a related plant community. This process enabled the assessment of the distribution with a finer resolution (5m x 5m) than the previous method. This combination and the multi-step workflow used for the analysis can be seen in *Figure 3* while a more detailed explanation can be found in *Appendix 2.3*.

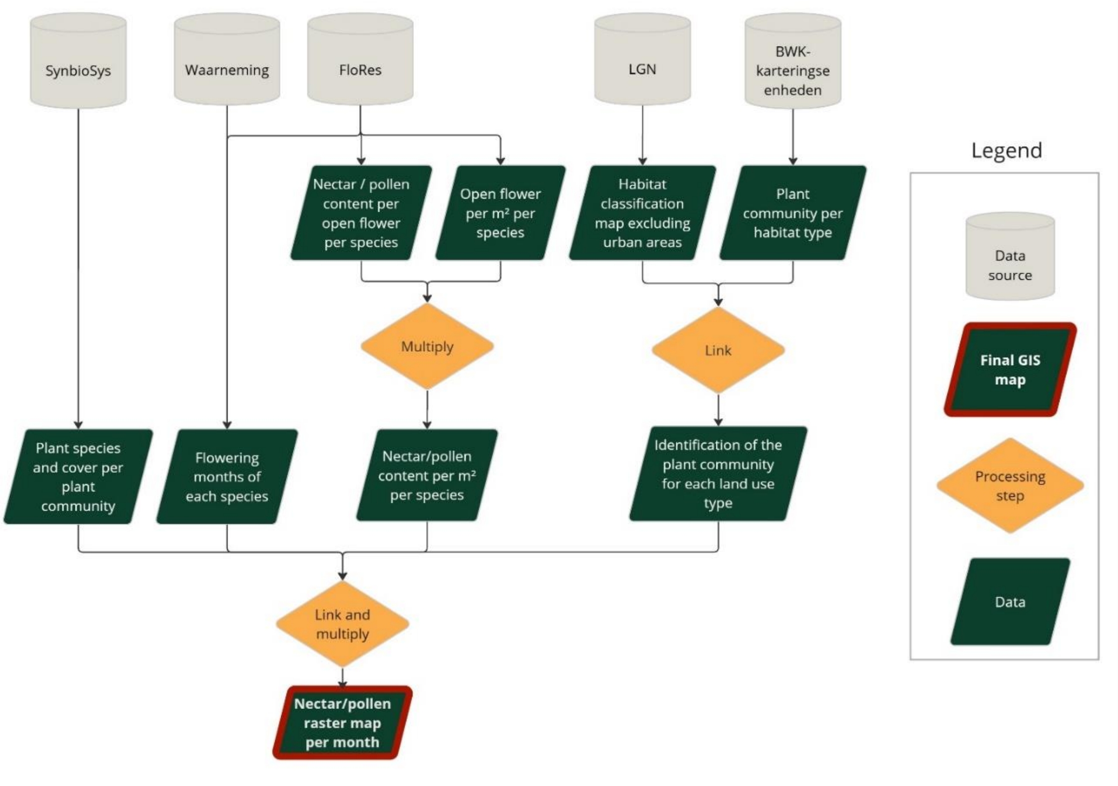

Figure 3: Workflow diagram of method 3: habitat classification. The links made between LGN and BWK-karteringseenheden is explained further in Appendix 2.3.

The land use map was obtained with the Landelijk Grondgebruik Nederland (LGN, 2021). This very detailed land use dataset was just made openly available on the 8th May 2023, and compiles 51 classes of natural, urban and agricultural areas. It combines multiple data sources itself to reach a resolution of 5m x 5m, which induces the method resolution. Each of these 51 classes was attributed (when possible) a habitat type using the 'BWK karteringseenheden' (see *Appendix 2.3*). This data was created by the Research Institute Nature and Forest of Flanders for creating a biological valuation map (Vriens et al., 2011). The BWK-karteringseenheden suggests for most land use types an associated Syntaxonomy (or plant community) taken from the 'Revisie Vegetatie van Nederlands'. The land use types are not corresponding exactly to the ones of LGN, and therefore for each class from LGN, a choice of which land use type from BWK fits best was made (e.g. 'Open stuifzand en/of rivierzand' was associated to 'Stuifduinen aan de kust'). When multiple BWK classes seemed applicable to a single LGN class, they were all selected and kept for the following steps. More detailed explanations are presented in Appendix 2.3 and all the associations made are listed in Supplementary data 3: PC_selected_per_LGN_class.

Once the plant communities were identified and linked to their respective land use types, the same process as in Method 2 was performed to combine SynBioSys and FloRes data into a table of nectar and pollen production per month for each land use type (see *Appendix 2.3*). When multiple BWK classes were linked to a single LGN one, an average of the production of the selected plant communities was made.

This table of results was then linked in ArcGIS to the LGN raster data. To allow for a join to be made, it required to use the 'Attribute table function' of the raster functions. The join was then made and a separate raster layer was created for each month for both pollen and nectar by using the 'Lookup' geoprocessing tool.

2.2.4 Method 4: Urban land uses classification.

While the importance of urban nectar resources for pollinators has been recognised (Tew et al., 2021), research on the spatial distribution of nectar in urban areas is scarce, with few studies conducted beyond field sampling.

In order to validate (or invalidate) the values obtained from the first two methods in urban areas, as well as combining the different outcomes, I utilised the nine urban land use classes model drawn by Tew et al. (2021) and inspired by Baldock et al. (2019). In this study, Tew et al. (2021) sampled nectar extensively in four British cities to identify an average nectar sugar production for each of these land use classes (e.g. cemeteries or parks). Due to data limitations, I used the assumption that a land use type possessed a similar floral composition in Dutch cities and in British cities, therefore allowing to make the link between the mean nectar values per square-meter of each land use class in the British cities and for the focus of this study. Therefore Dutch cities were classified in these nine classes through multiple databases. As the 'manmade surface' class was providing zero nectar production, it was not considered and focus was made on the eight other classes. The visualisation of the overall process of this method can be found in *Figure 4*.

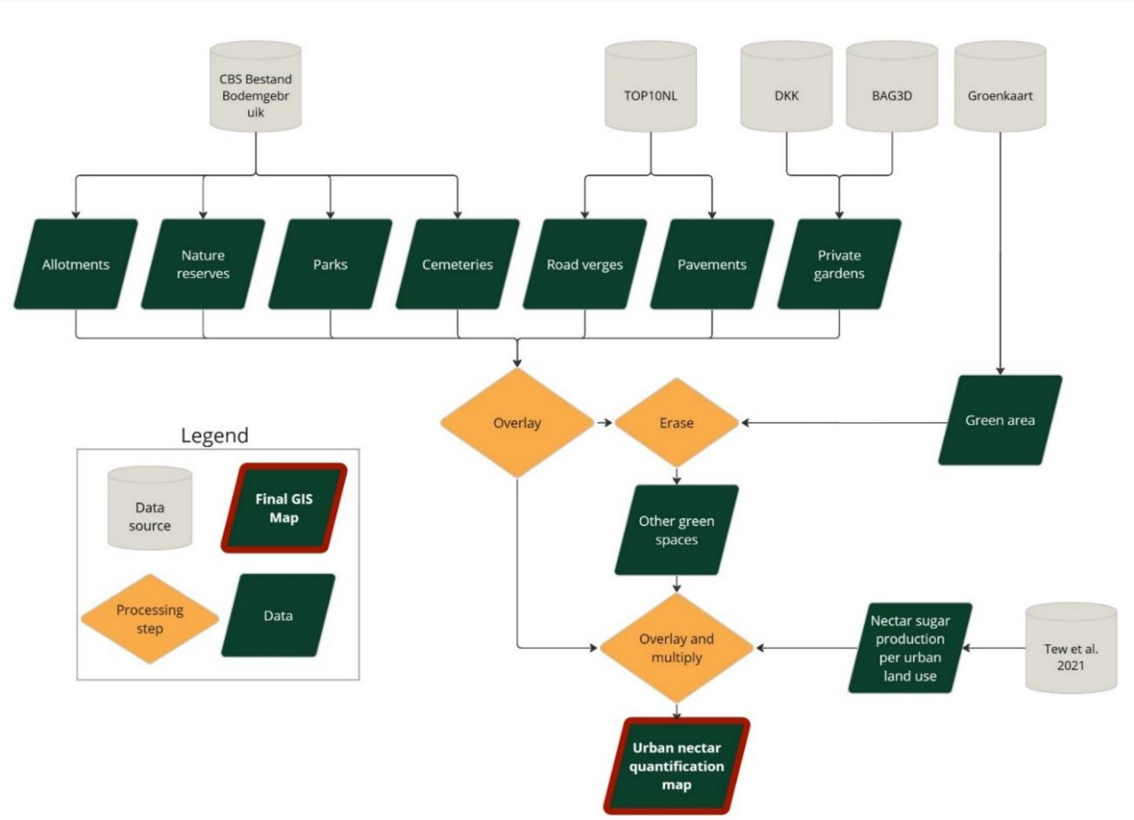

Figure 4: Workflow diagram of method 4: urban land uses classification.

To accomplish this, the data sources employed to identify the eight distinct classes of land use types, were CBS BBG (CBS, 2017), TOP10NL (BRT, 2023), DKK (ESRI Nederlands, 2023) and BAG3D (ESRI Nederlands, 2020) as outlined in *Table 2.* The selection of whether an area is part of urban area or not has been made using the TOP10NL Plaats_vlak layer. This layer contains the land use footprint for concentrated built-up area (*bebouwde kom*) for the Netherlands. All data layers presented after have been framed to this selection. Conversely to the other methods, no monthly data and no pollen production data were found for urban areas. This method therefore yields into a single annual nectar production map for urban areas.

Table 2: Database sources and specific layer used to obtain each of the eight urban land use classes defined by Baldock et al. (2019) and used in method 4: urban land uses classification.

URBAN LAND USE	SOURCE	URBAN LAND USE	SOURCE
Allotments	CBS BBG class 42	Pavements	TOP10NL Wegdeel_vlak
Nature reserves	CBS BBG class 61&62	Road verges	TOP10NL Wegdeel_vlak
Parks	CBS BBG class 40	Private gardens	DKK, BAG3D
Cemeteries	CBS BBG class 32	Other green spaces	Groenkaart

Specifically, the classes **Allotments**, **Nature reserves**, **Parks** and **Cemeteries** were directly derived from CBS BBG, with the correspondence of classes being selected by comparing the descriptions of CBS classes and the urban land use classification from Baldock et al. (2019) (*Table 2)*. **Pavements** were derived from the TOP10NL Wegdeel_vlak layer for which roads where the 'verhardingstype' was paved were selected. **Road verges** were constructed starting from the same layer, but only the main roads (lokale, regionale, hoofd- and autosnel- weg) were selected. A 5-meter-large buffer was then made and overlaps were deleted. **Private gardens** were obtained from a combination of the cadastral map DKK and the buildings layer BAG3D. Only the parcels containing a residential building were selected and the latter was removed from the area. A limited amount of parcels had unrealistic areas which were deleted from the final data when bigger than 100 hectares. **Other green spaces** were defined from the Groenkaart layer (RIVM, 2020) from which all other layers were removed. The Groenkaart is a raster map delivering a value of greenness percentage of the area with a 10m x 10m resolution made by RIVM and Atlas van Natuurlijk Kapitaal, which was binarised to differentiate green and non-green areas. The more detailed processes used to obtain the data can be found in *Appendix 2.4*.

All these urban areas were then manually given a nectar value based on which class it belongs to and the data from Tew et al. (2021). The data processing has been made with polygon shape files, and turned into rasters after the processing has been completed. These raster were aggregated from fine scale resolution (1m x 1m or 5m x5m) to 100m x 100m. The raster maps of each land use classes were then overlaid by summing up their respective values, as the multiple classes happen within the same cell.

In order to allow for better comparison with method 4, the first three methods were also averaged over the months. This allows for an extra angle of reading the results through a month-independent hotspot analysis.

2.2.5 Method 3+4: combination of methods 3 and 4.

The last two methods, assessed as the most promising ones by experts (see *Appendix 3*) were then overlaid to obtain a map where both urban and non-urban areas were covered. This will be referred to as Method 3+4. As the fourth method was the most limiting of both, the combination was fitted to the properties of method 4. This means it only entails the nectar sugar production and the resolution is 100m x 100m on a yearly basis. The monthly data from method 3 was averaged to a yearly map to allow the results to be matched.

For the overlay, the data was combined with giving a priority to the urban results. Therefore, the non-urban data from method 3 comes as a supplementary to method 4 everywhere the urban results yield into a zero value. As no data was given in method 3 in urban areas, a simple sum could have been performed but this has been decided to also fit further work that would include plant communities (and therefore nectar production) in some urban areas for method 3 and to prevent inconsistencies in the definition of urban areas. This was performed through the raster calculator. The process is shown in *Figure 5*.

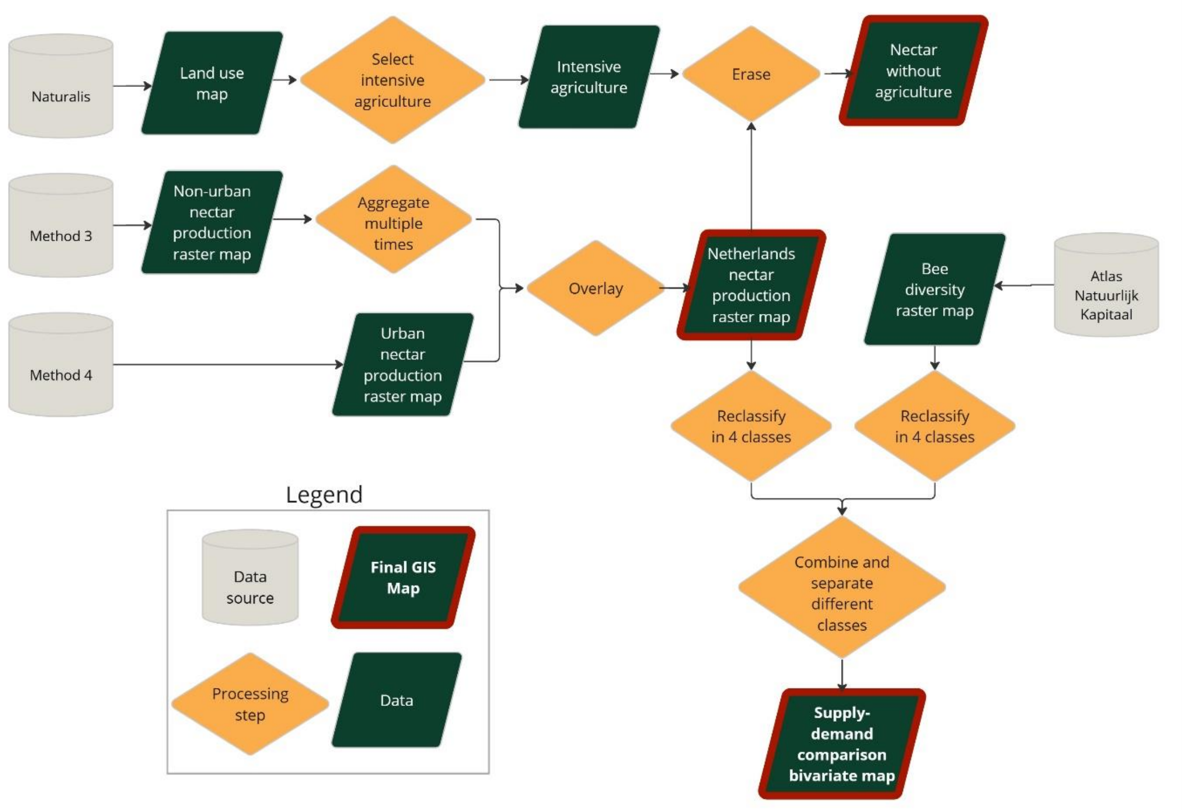

Figure 5: Workflow diagram of method 3+4 and the comparison with bee diversity.

As plant communities were assessed to be an idealistic view, especially for agricultural fields, a comparison was made for the results of method 3+4 with removing the data for all intensive agricultural fields. This was made through the use of a land use map made by Leon Marshall from Naturalis. From this land use map, intensive agriculture was defined as food and non-food crops, food grasslands and greenhouses (*Figure 6*). Intensive agriculture plays a substantial role in the Dutch agricultural sector, although it is important to note that the estimation of its exact extent here showcased may still be approximate. This intensive agriculture footprint was then erased through the raster calculator from the results of method 3+4.

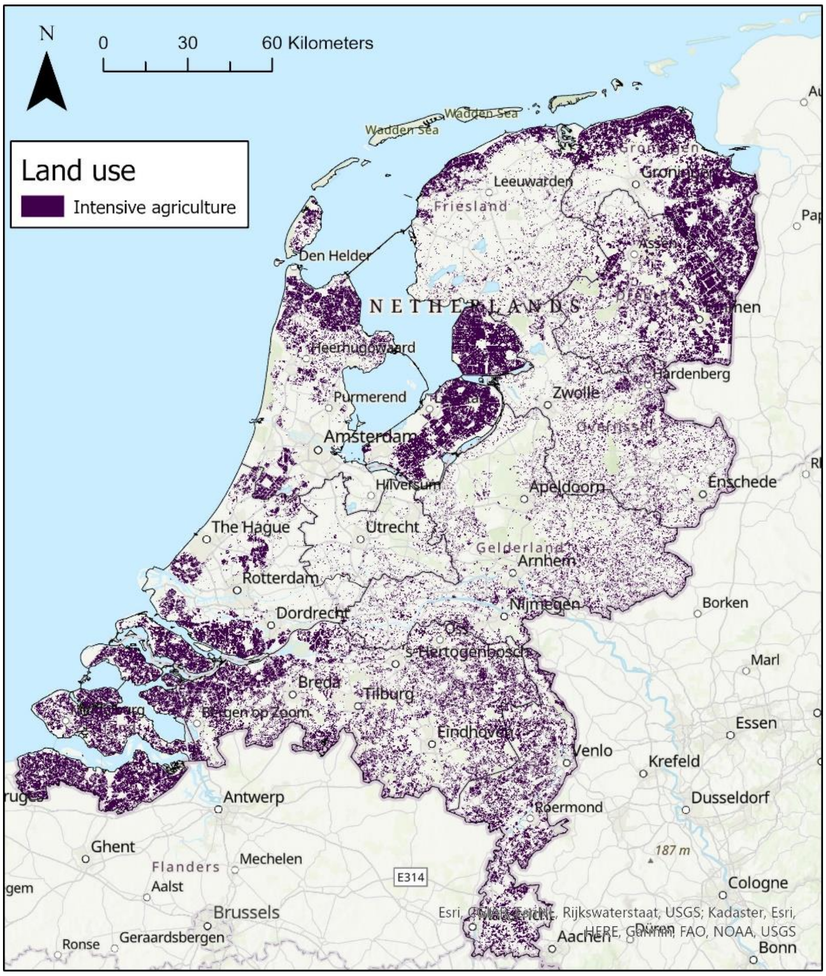

Figure 6: Spatial distribution of the intensive agricultural areas of the Netherlands. This includes crops, grasslands for food purposes and greenhouses.

2.3 Comparison with pollinators presence

The map obtained from the former subsection combining the results of method 3 and 4 was then analysed next to the 'Bijendiversiteit' map (RIVM, 2017). This bee diversity map was created by Leon Marshall from Naturalis who combined field observations with a large variety of parameters (e.g. land use or precipitation) including food availability through expert judgement by Koos Biesmeijer. The food availability modelled in this study is then compared to a bee diversity already dependent on some kind of food availability indicator, requiring critical awareness when discussing implications of such comparison (see *Section 4.7*). The process used can be found in *Figure 5*.

In details, both layers of bee diversity and nectar production were reclassified into four distinct classes. They were then combined for each couple of values to be a different value before being displayed as a bivariate map. The classification used for the two variables while making the bivariate map is listed in *Table 3*.

Table 3: Classification of the bee diversity and nectar sugar production chosen for Figure 23-Figure 24.

CLASSIFICATION	LOW	MIDDLE-LOW	MIDDLE-HIGH	HIGH
Bee diversity (number)	0-10	10-40	40-80	>80
Nectar production (mg/m²/day)	0-5	5-20	20-150	>150

3.Results

3.1 Results of each method

3.1.1 Method 1: Richness map and attractiveness weighting.

The first method results in a month-by-month raster map of the attractiveness index, covering the scale of the Netherlands (*Figure 7*). It provides information on the relative attractiveness of areas to pollinators in terms of food availability by comparing environments based on the richness of the most highly visited plant species.

Attractiveness to pollinators

A main trend appears in a major part of the country, with an increasing attractiveness until July and August before exhibiting a steady decline until the end of the year. The highest value is reached mostly in the South of the Netherlands, specifically in the provinces of North Brabant and Limburg. The natural areas (e.g. Veluwe) do not appear as attractive areas for pollinators, through lower attractiveness than their surroundings most of the time, except in the month of October. This is due to a delayed end of flowering of the species considered in these areas. In January and February the distribution seems to be divided into a West/East division of the Netherlands, however regarding these months only one plant considered in the study is blooming (*Bellis perennis*). Therefore the distribution of the attractiveness index is directly dependent on its distribution and no relevant conclusions should be drawn.

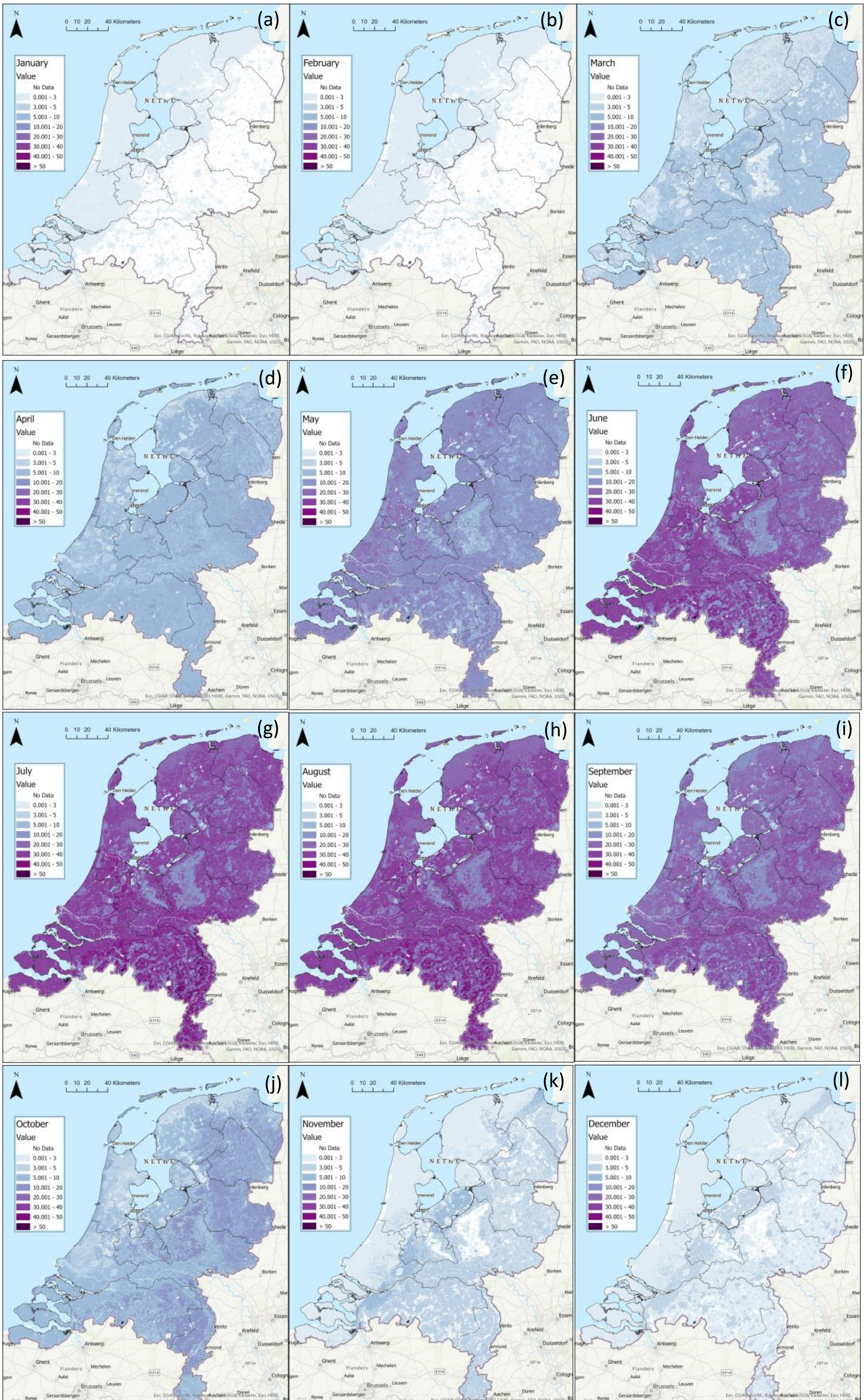

Figure 7: Monthly Attractiveness Index for pollinators, representing the relative appeal of areas to pollinators, depicted for each month of 2022 from (a) to (l). To ensure comprehensive representation of the full range of

values throughout the year, narrower classes were used for low attractiveness, while larger classes were used for high attractiveness, all presented on a consistent scale. Larger versions of the individual maps can be found in Appendix 4.1, and an animated figure in the form of a GIF is available in Supplementary data 1: Method1FinalTop44.gif.

Maximum and average attractiveness

Similar to the previous findings, investigating the maximal attractiveness index reveals a consistent upward trend in pollinator attractiveness from the beginning of the year until July, followed by a gradual decline until December (*Figure 8)*. The average attractiveness index across the country also exhibits a similar pattern. It should be noted that while the overall trend aligns with observations in many parts of the Netherlands, it is possible for certain areas to exhibit different distribution patterns.

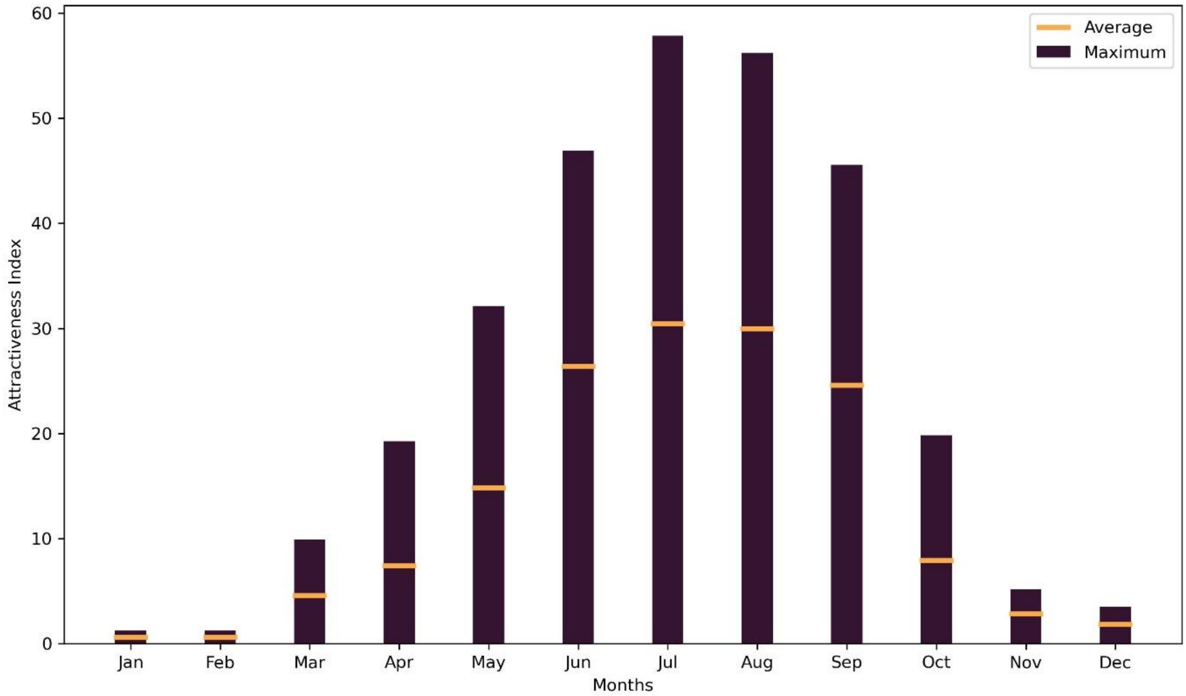

Figure 8: Evolution of the maximal and average attractiveness index per month in the Netherlands in 2022. This figure informs on the monthly levels of attractiveness overall without giving insights in any spatial trends.

Yearly average

When considering the yearly average of attractiveness, it becomes apparent that natural areas (e.g. Veluwe) show relatively lower attractiveness compared to the rest of the Netherlands (*Figure 9)*. Other areas, although lower in attractiveness, are more scattered throughout provinces like Drenthe, North Brabant, Limburg and along the coast in North Holland. Notably, the provinces of North Brabant and Limburg exhibit a constrasting pattern, with some areas being the most attractive while others are the least attractive areas.

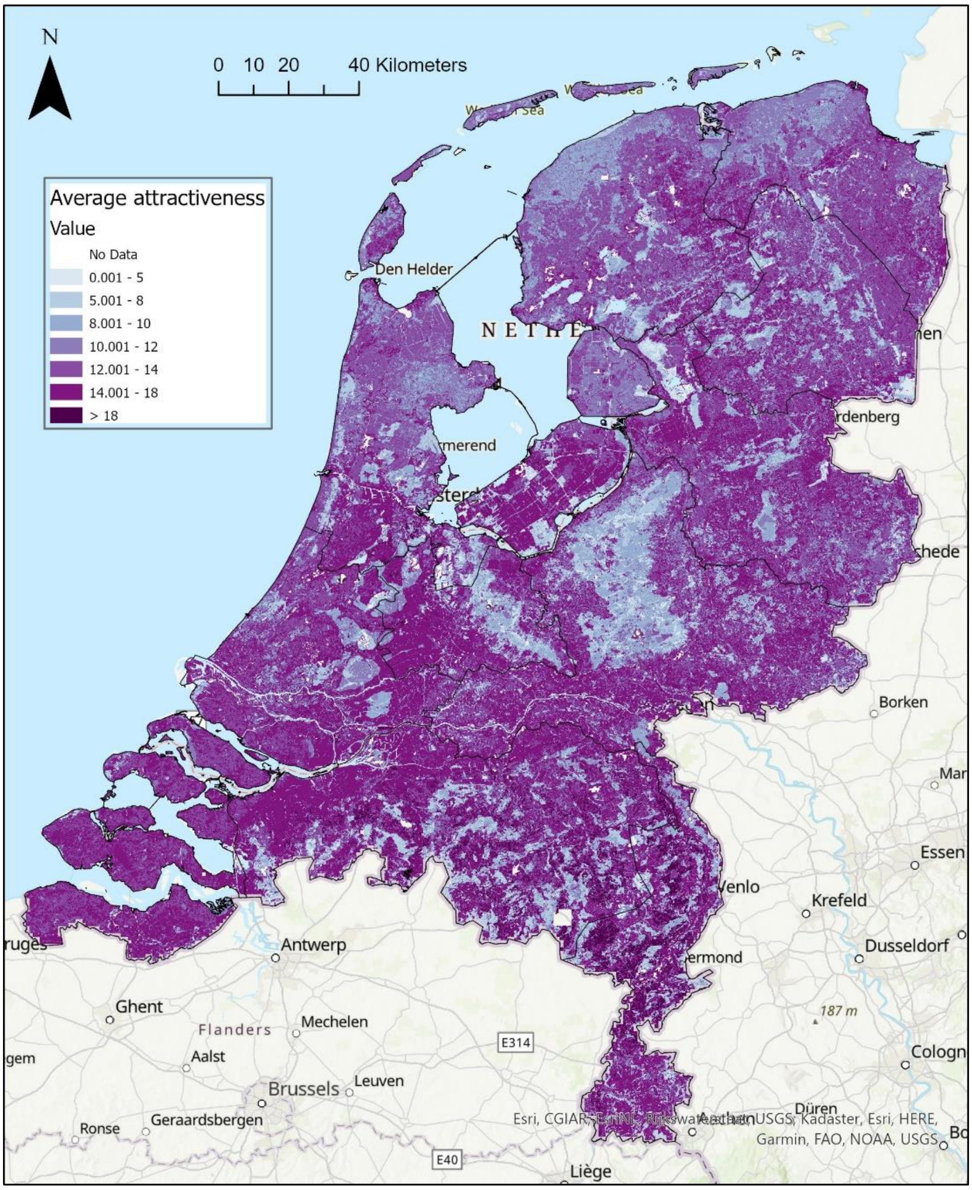

Figure 9: Yearly average of the pollinator attractiveness index across the Netherlands in 2022.

3.1.2 Method 2: Plant communities distribution.

The results of the second method are month-by-month maps for both nectar sugar production and pollen. This set of maps has been compiled in *Figure 10* for nectar, and *Figure 11* for pollen.

Nectar sugar production

Regarding nectar sugar production, March stands as the first month where a bump in the production can be witnessed, and a peak of 2711 mg/m²/day is reached in May. Similarly to the first method, one can identify a later nectar production increase in the natural areas (see Veluwe) as well as in Drenthe around August. This is lasting until October while the other areas already exhibit important declines in September. It is important to note that the distribution for the months of December and January is based on the presence of only one species, which limits the ability to draw clear conclusions. The province of South Holland emerges as a region with high production levels, both during months of low production (e.g. November) and months of high production (March to August).

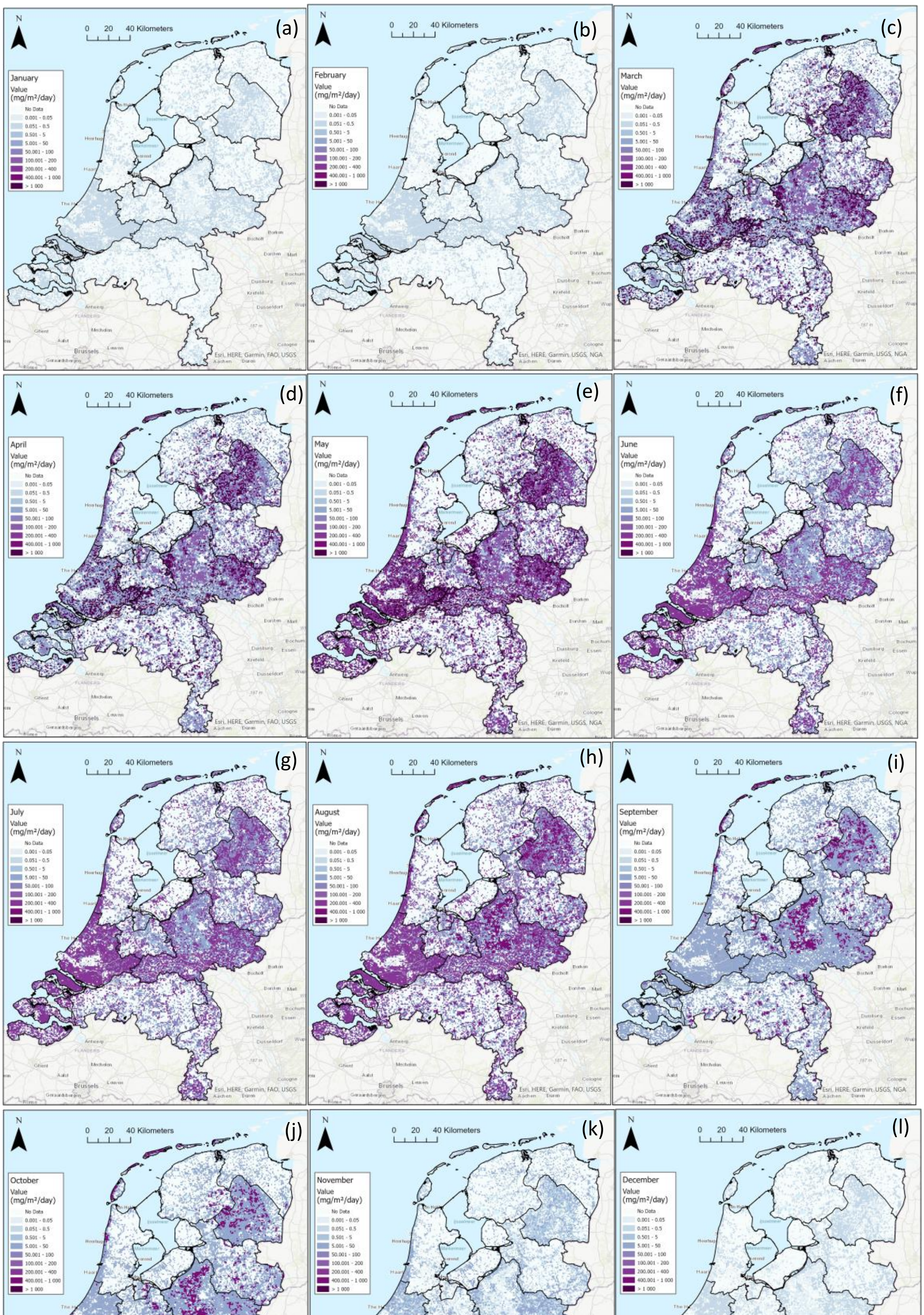

Figure 10: Daily availability of nectar sugar in the Netherlands in 2022 based on method 2: plant communities distribution. The figure displays the monthly variations in nectar sugar availability per day. Each panel

corresponds to a specific month, spanning from (a) to (l). To ensure comprehensive representation of the full range of values throughout the year, narrower classes were used for low availability, while larger classes were used for high availability, all presented on a consistent scale. Larger versions of the individual maps can be found in Appendix 4.2, and an animated figure in the form of a GIF is available in Supplementary data 2: Method2_final_nectar.gif.

Pollen production

One can observe a heavy increase in the pollen production for the months of March to May with high production values in the areas of South Holland, Drenthe and Veluwe similarly to what was observed for nectar. However regarding pollen production, the following months (June to August) are much more stable in terms of production, and evenly distributed over the study area. The production shows a major decrease compared to the spring months but remains in the same order of magnitude from June to October for most areas. In absolute terms the production of pollen is higher than the one of nectar sugar with values ranging up to 7000 mg/m^2/day.

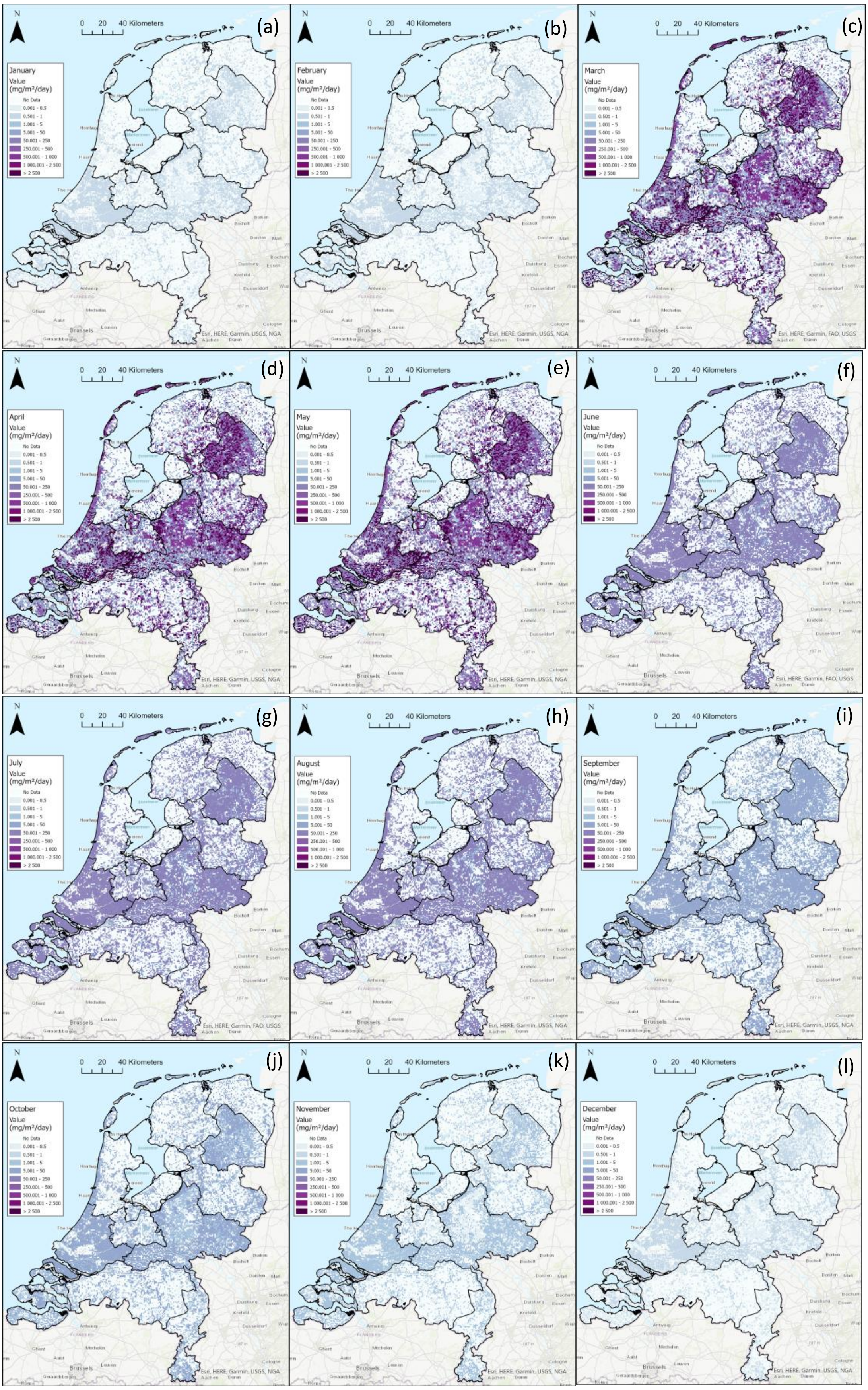

Figure 11: Daily production of pollen content in the Netherlands in 2022 based on method 2: plant communities distribution. The figure displays the monthly variations in pollen availability per day. Each panel corresponds to a specific month, spanning from (a) to (l). To ensure comprehensive representation of the full range of values

throughout the year, narrower classes were used for low production, while larger classes were used for high production, all presented on a consistent scale. Larger versions of the individual maps can be found in Appendix 4.3, and an animated figure in the form of a GIF is available in Supplementary data 2: Method2_final_pollen.gif.

Maximal and average production

Upon examining the evolution of maximal and average production over the months (*Figure 12*), similar observations can be made. The maximum and average production exhibit analogous trends throughout the months. It is important to note that this figure solely presents the maximal and average production and does not provide information on the trends in specific areas. As previously mentioned, the Veluwe area serves as a good example: it demonstrates a peak production in August, September and October, which can be attributed to a delayed flowering pattern in this area and therefore does not follow a similar curve.

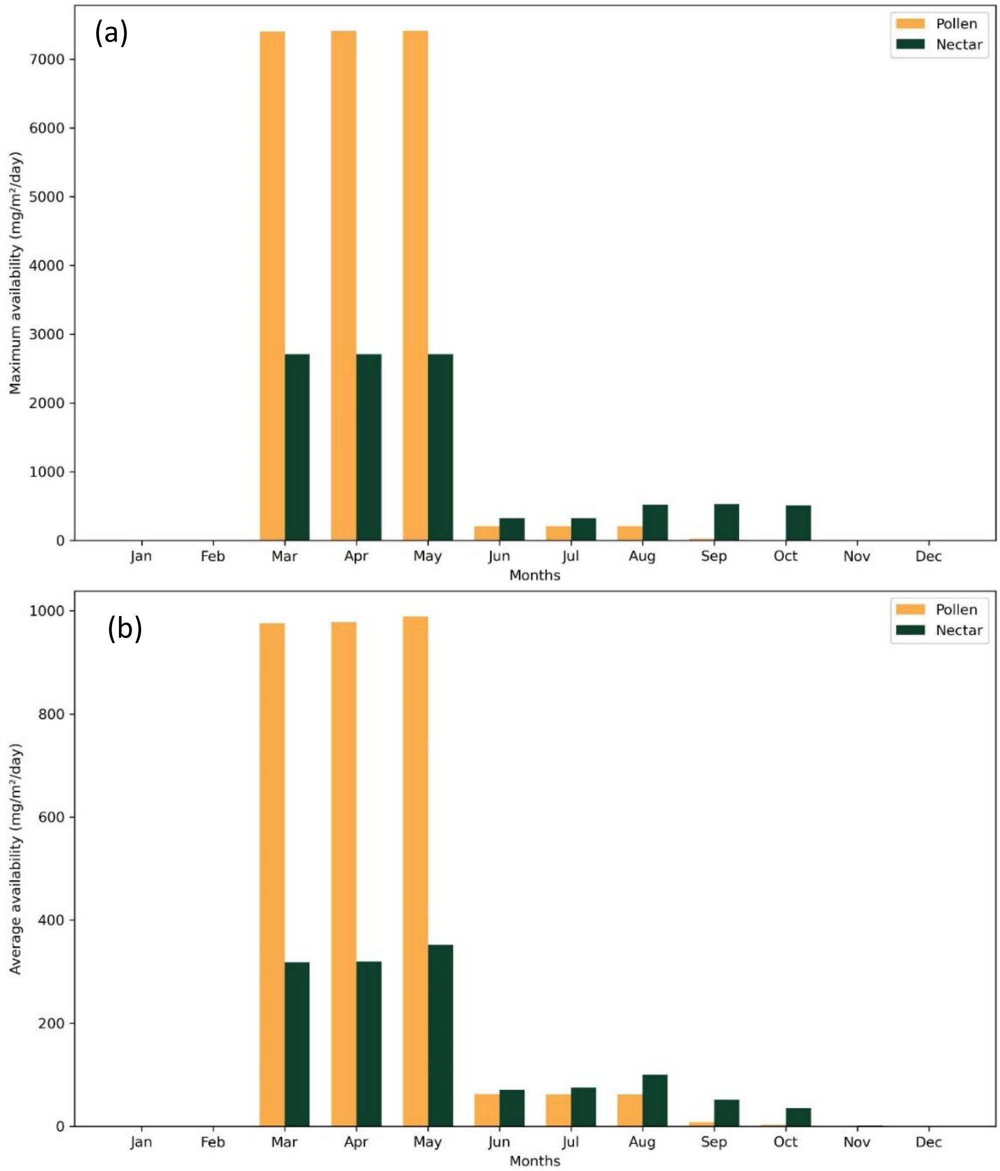

Figure 12: Evolution of the maximal (a) and average (b) availability of pollen and nectar over the months across the Netherlands in 2022, based on method 2: plant communities distribution. This figure informs on the monthly levels of floral resources availability overall, and compares the production levels in nectar sugar content and pollen without giving insights in spatial trends.

Yearly average

Comparably to what the monthly maps have shown, one can observe a similar distribution of the nectar and pollen production when looking at the yearly average maps presented in *Figure 13*. This makes sense considering the way these maps were made, but some minor differences show up due to the differences of production value of nectar against pollen of the different plant species considered. Interestingly in absolute terms, the difference in nectar and pollen production is reduced: the mean of the yearly nectar production is about 1122 mg/m²/day while it is 2691 mg/m²/day for pollen production (values provided by the statistics function in ArcGIS).

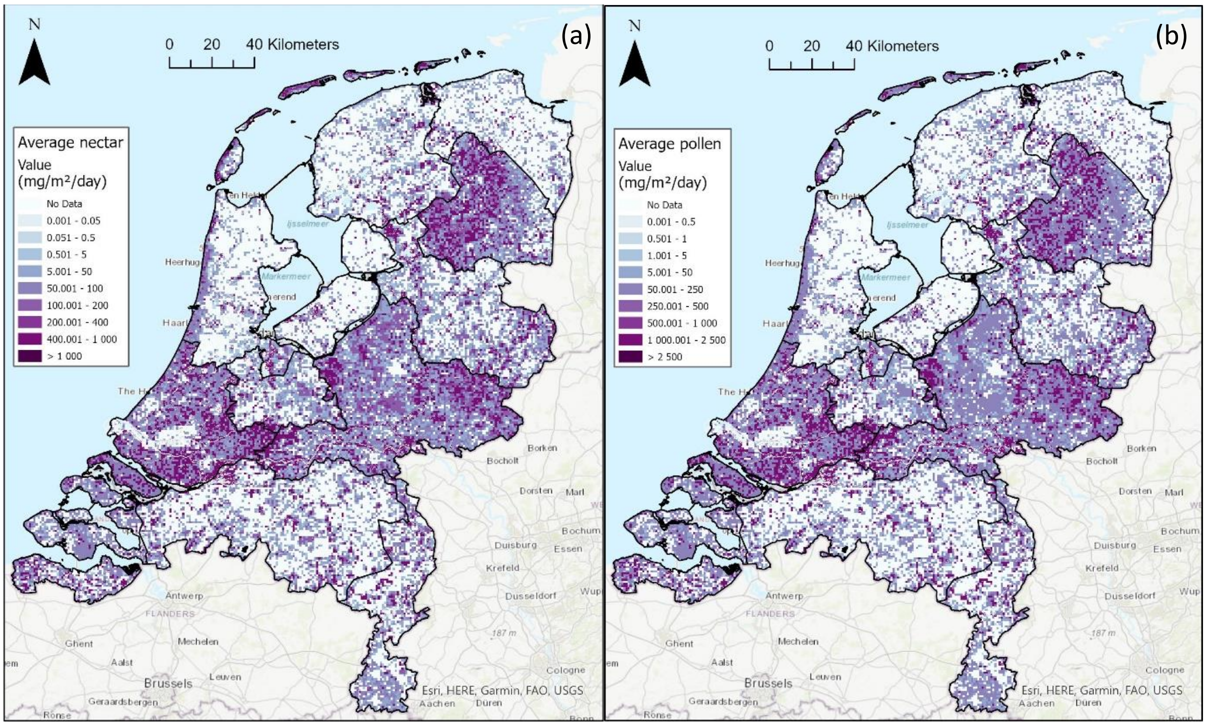

Figure 13: Yearly average of the nectar sugar (a) and pollen (b) production across the Netherlands in 2022 using method 2: plant communities distribution.

3.1.3 Method 3: Habitat classification.

The results of the third method are month-by-month maps for both nectar sugar production and pollen. This set of maps has been compiled in *Figure 14* for nectar, and *Figure 15* for pollen.

Nectar sugar production

A noteworthy finding in this method is the significant increase in nectar production primarily occurring in April. The natural coastal areas, including Oostvaardersplassen and the dunes, exhibit a peak production in March and April. It is important to consider that the smaller size and finer resolution of these areas may make this peak easily overlooked. In contrast, another prominent peak of nectar production is observed in September in the Veluwe area, as well as in North Brabant, Limburg and some parts of Drenthe. The areas showing no nectar production match urban areas, for which no specific plant community was assigned. This highlights the value of integrating multiple methods (see *Section 3.1.5*). Additionally, it is noteworthy that agricultural areas exhibit a later peak in nectar production compared to other regions.

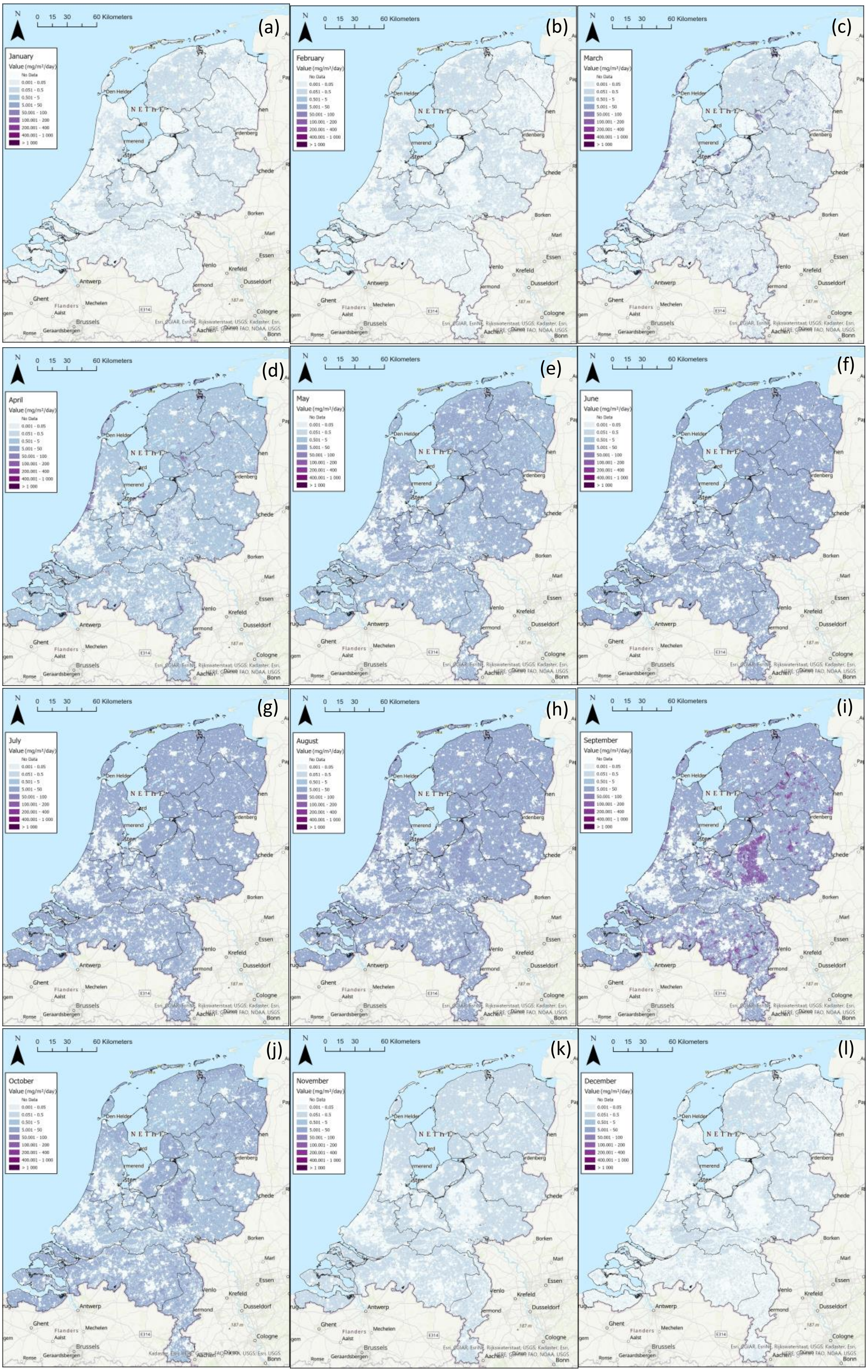

Figure 14: Daily availability of nectar sugar in the Netherlands in 2022 based on method 3: habitat classification. The figure displays the monthly variations in nectar sugar availability per day. Each panel corresponds to a specific

month, spanning from (a) to (l). To ensure comprehensive representation of the full range of values throughout the year, narrower classes were used for low availability, while larger classes were used for high availability, all presented on a consistent scale. Larger versions of the individual maps can be found in Appendix 4.4, and an animated figure in the form of a GIF is available in Supplementary data 3: Method3_final_nectar.gif.

Pollen production

The natural coastal areas exhibit a high pollen availability early in the year, particularly in March. This peak production is strongly influenced by Salix species, which are highly present, have high nectar and pollen production values and flower between March and April. In April, a significant portion of the Netherlands shows increased pollen production, which continues to rise steadily until reaching a relatively stable level between June and September. Interestingly, the Veluwe area, which also contains Salix species, experiences an increase in pollen production in march. However, this production diminishes from May onwards, resulting in the area becoming a “coldspot” for pollen availability.

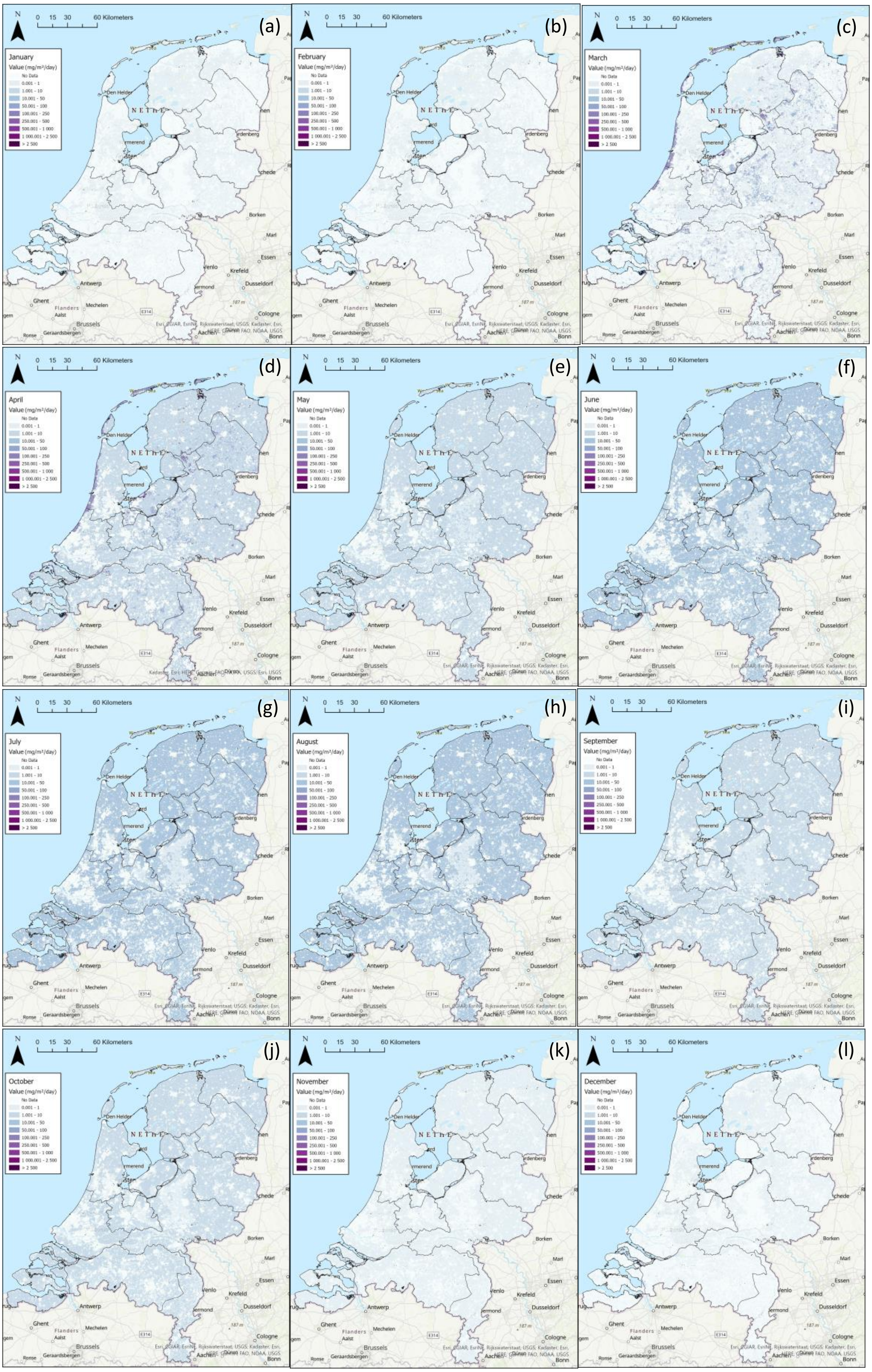

Figure 15: Daily production of pollen content in the Netherlands in 2022 based on method 3: habitat classification. The figure displays the monthly variations in pollen availability per day. Each panel corresponds to a specific

month, spanning from (a) to (l). To ensure comprehensive representation of the full range of values throughout the year, narrower classes were used for low production, while larger classes were used for high production, all presented on a consistent scale. Larger versions of the individual maps can be found in Appendix 4.5, and an animated figure in the form of a GIF is available in Supplementary data 3: Method3_final_pollen.gif.

Maximal and average production

The maximal production per month show similar results to the second method (*Figure 16)*. Pollen production presents one major peak of about 7000 mg/m²/day in March, April while being very low the rest of the months considered. Nectar production on the contrary has two clear peaks of production, the biggest one being the same months as pollen with about 2400 mg/m²/day while a second lower peak appears in August and September of about 700 mg/m²/day. However, compared to the second method here the peak only lasts until April and a huge decrease appears for the month of May. It is interesting to mention that on a much lower scale, an increase in pollen production is still witnessed in June, July and August (from about 10 mg/m²/day to 45 mg/m²/day).

In contrast to the previous findings, this method reveals distinct patterns between average and maximum nectar and pollen availability. The average availability of pollen exhibits a peak in March and April, followed by a decrease in May. It then increases during the summer months before gradually declining in autumn. Similarly, nectar availability experiences a ‘May gap’ with a temporary decrease before gradually increasing and reaching its peak in September, after which it declines rapidly. Notably, the average availability is much lower compared to the results obtained from method 2, with an average value of around 10 mg/m²/day.

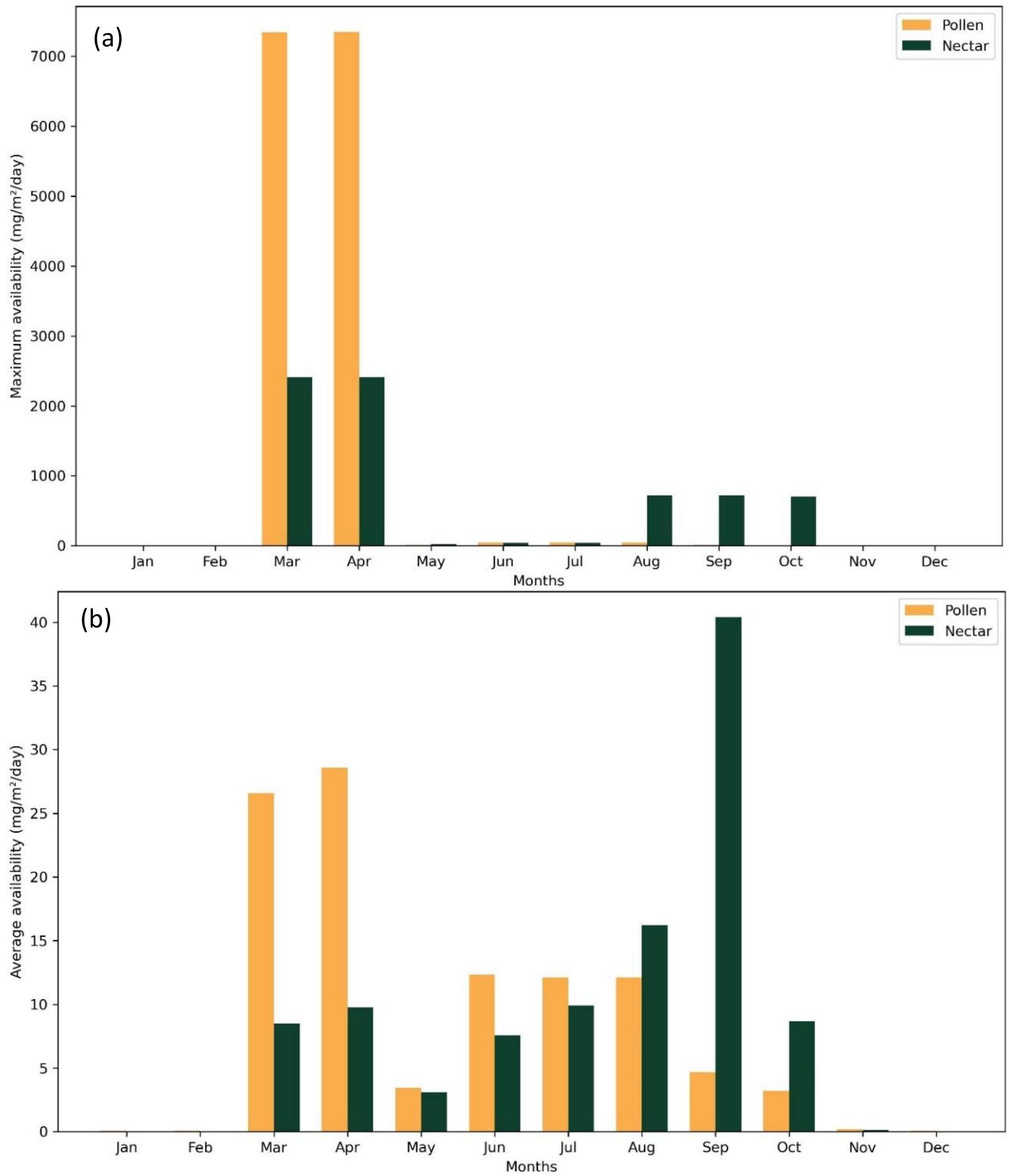

Figure 16: Monthly evolution of maximal (a) and average (b) production of pollen and nectar in the Netherlands in 2022, based on method 3: habitat classification. This figure informs on the monthly levels of floral resources availability overall and compares the pollen and nectar production without giving insights in any spatial trends.

Yearly average

When averaging the monthly maps to a single yearly nectar and pollen production, different patterns appear. *Figure 17* depicts the results and highlights the specific hotspot of nectar and pollen production in Oostvaardersplassen. Most areas show similar patterns in both nectar and pollen production but the Veluwe area strikes as an outlier. Due to its presence in both nectar peaks of production (March and September), it is a slightly above average producer of nectar while conversely, it appears to perform below average in terms of pollen production on average. As seen in the former subsections, the pollen production in the Veluwe area appears for the months of March and April, but the rest of the months are underproducing compared to its surroundings, hence these results.

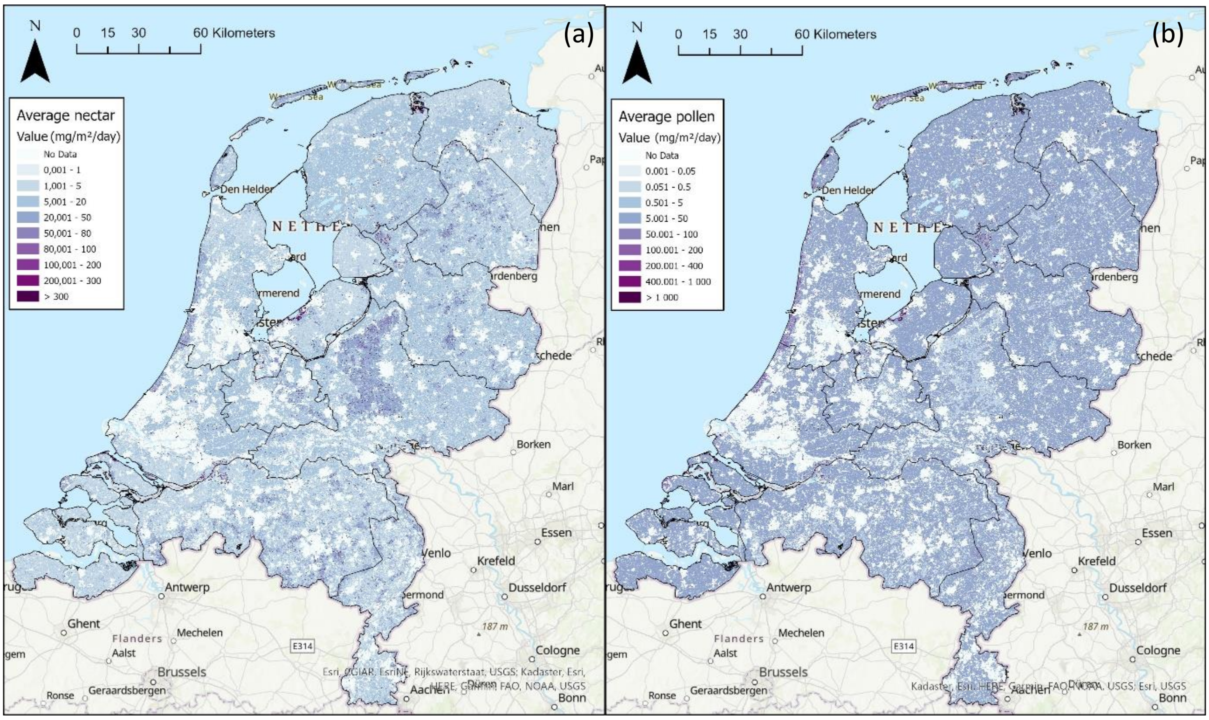

Figure 17: Yearly average of the nectar sugar (a) and pollen (b) production across the Netherlands in 2022 using method 3: habitat classification.

3.1.4 Method 4: Urban land uses classification.

Conversely to the other methods, this method yields into a single annual map of nectar sugar production. It therefore does not include a similar bar chart of maximum and average availability. *Figure 18* depicts the results of the fourth method on urban nectar production.

The values of urban nectar sugar production range from zero to a maximum of 16.5 mg/m²/day. This is close to twice as much as the maximal production obtained by Tew et al. (2021) which was 8.988 mg/m²/day for private gardens and is about the sum of both private gardens and allotments values. This indicates that some overlap between these two layers appeared and thus double counting, particularly between private gardens and allotments or parks. Indeed, if the data were perfectly separated, the highest production would be 8.988 mg/m²/day for a 100m x 100m cell entirely covered by private gardens.

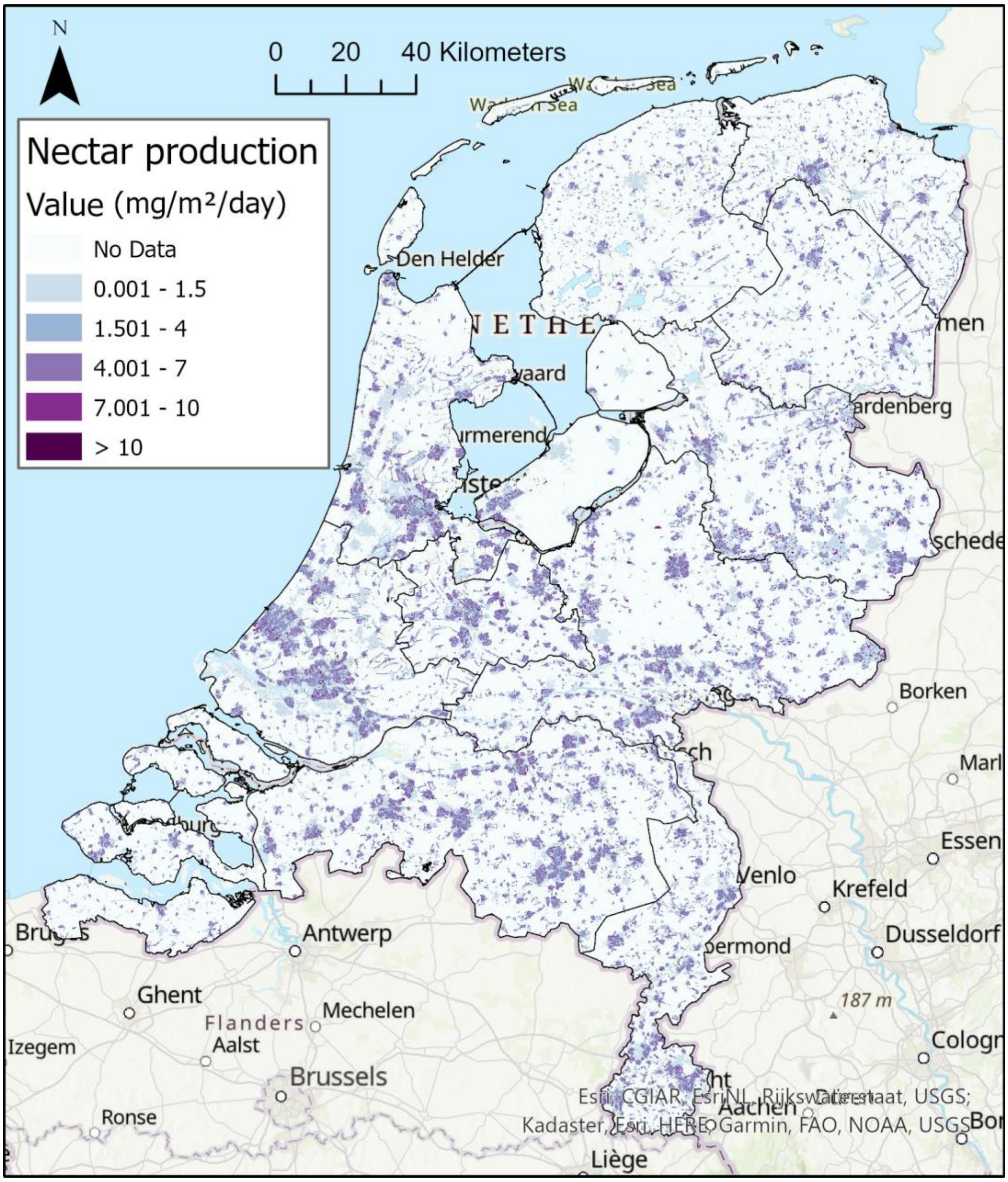

Figure 18: Nectar sugar production of urban areas in the Netherlands in 2022, based on method 4: urban land uses classification.

For clearer understanding of these results, a focus on the municipality of Amsterdam was highlighted in *Figure 19*. One can therefore identify the highest production areas and validate based on their land use: in the south of Amsterdam Zuid-Oost is highlighted a golf course, showing that this golf course was selected as a private garden. A bit more North just on the side of Diemen, the combination of de Park de Meer and a cemetery are reasons for the high nectar production. The boundaries of what was defined as urban area are also clearly identifiable as for example some areas of the Westpoort, or in the North-East the areas of Randorp and Zunderdorp. Both are represented by a small city center included in urban areas, but the surroundings were excluded.

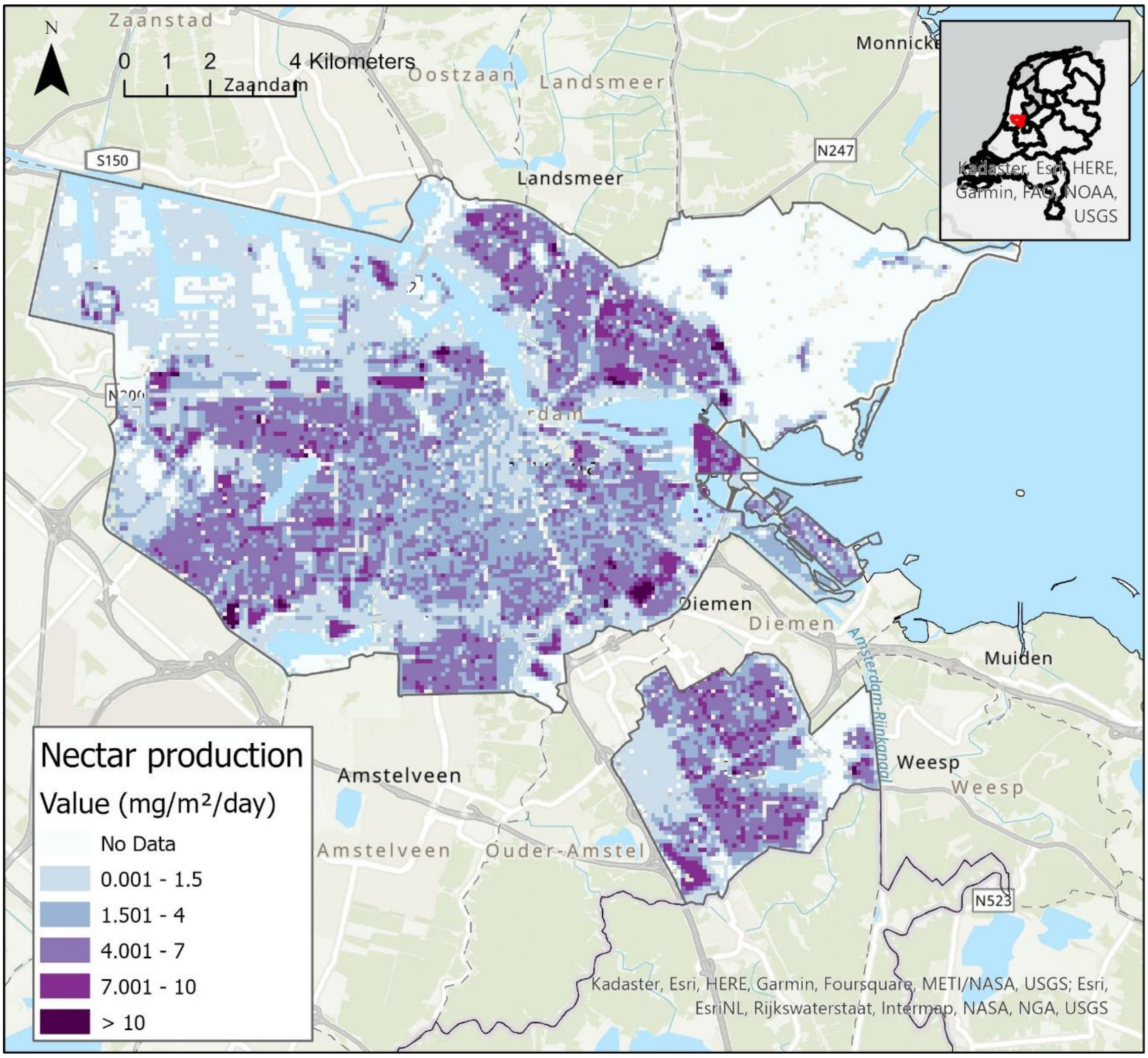

Figure 19: Nectar sugar production in the municipality of Amsterdam in 2022, based on method 4: urban land uses classification.

3.1.5 Method 3+4: combination of methods 3 and 4.

Looking at method 3+4, one can observe a fairly distributed nectar production with specific locations with a higher production, mainly the high production areas identified in Method 3 (*Figure 20)*. Indeed, the nectar production of urban areas being below 16.5 mg/m²/day, the main hotspots of nectar production are highly influenced by those of method 3. The ones standing out the most are Oostvaardersplassen, the wetlands of Kalenberg and the water reserve of Lauwersmeer. Some urban areas remain with no or very low nectar production (e.g. Leeuwarden, Alkmaar). It should be kept in mind that the definitions of urban areas are similar and based on the same layer for both methods 3 and 4, but are not strictly the same. Therefore some very low nectar production areas are still considered urban areas.

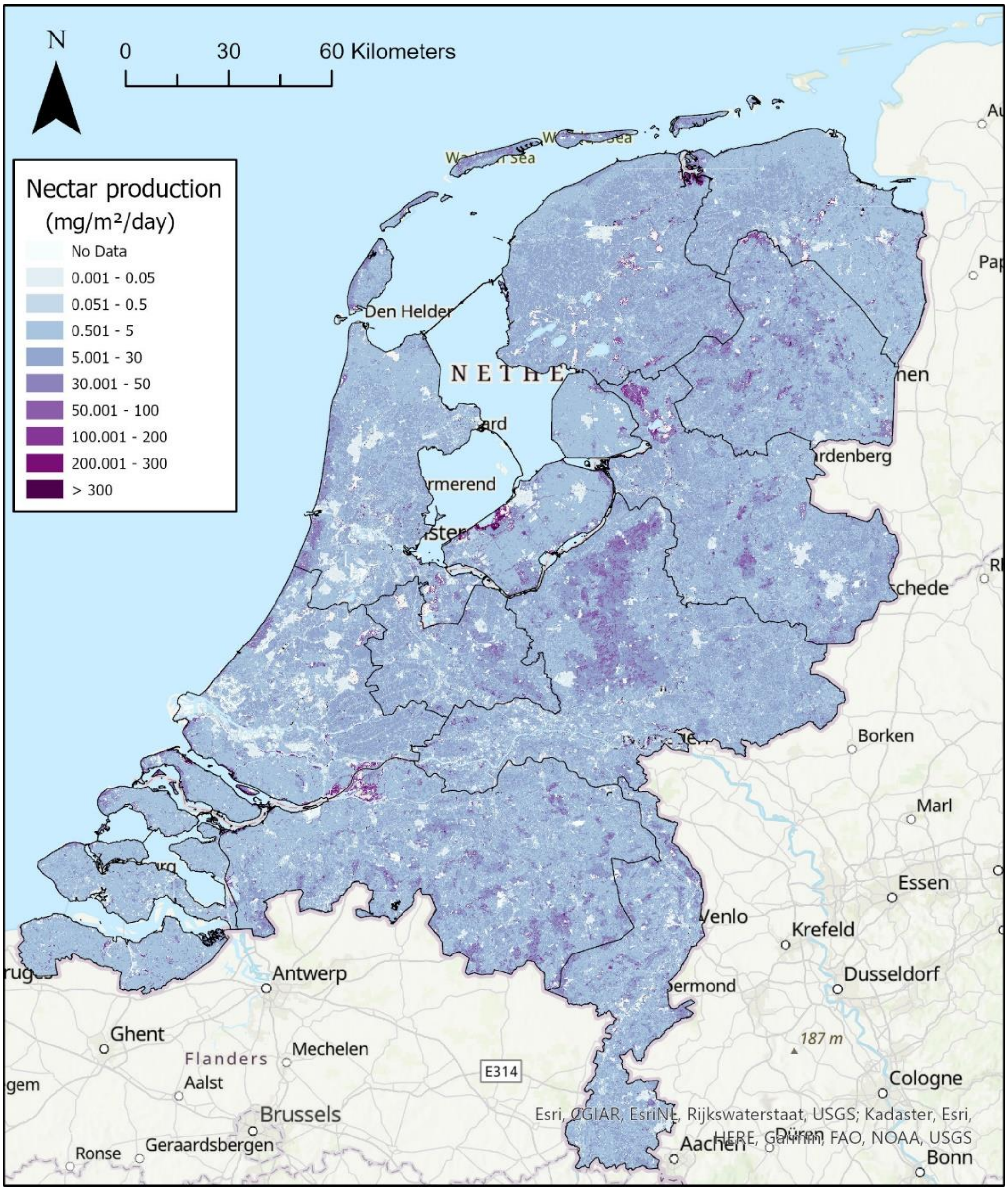

Figure 20: Nectar sugar production in the Netherlands in 2022 resulting from method 3+4.

Similarly to what was made for method 4, an inset look in the municipality of Amsterdam is shown in *Figure 21*. One can observe the areas around Ransdorp and Zunderdorp which were not included in method 4 have been filled up by data from method 3. The rest of the municipality is overall quite evenly distributed as well, with slight patches of higher production in the Western and Eastern extremes of the municipality. Looking at what land use is there, this makes sense as the most eastern point represents a natural reserve and the western part represents the wetlands of De Groote Braak.

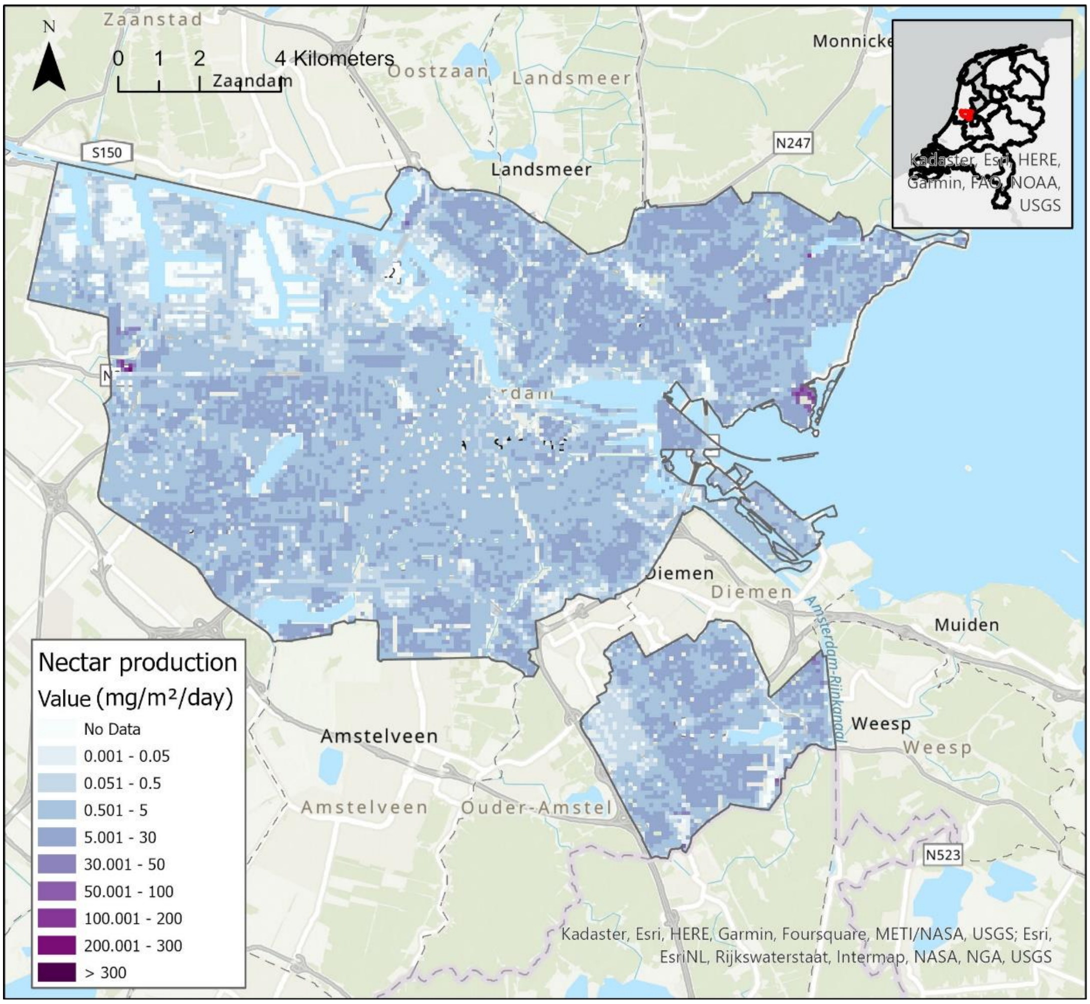

Figure 21: Nectar sugar production in the municipality of Amsterdam in 2022, based on the combination of methods 3 and 4.

The same nectar sugar production is depicted in *Figure 22* but without the intensive agricultural fields. This is intended to shed light on the large portion of the Netherlands where intensive agricultural fields hinder the availability of nectar. As presented in *Section 2.2.5*, the main difference appears in the provinces of Flevoland and Zeeland among others.

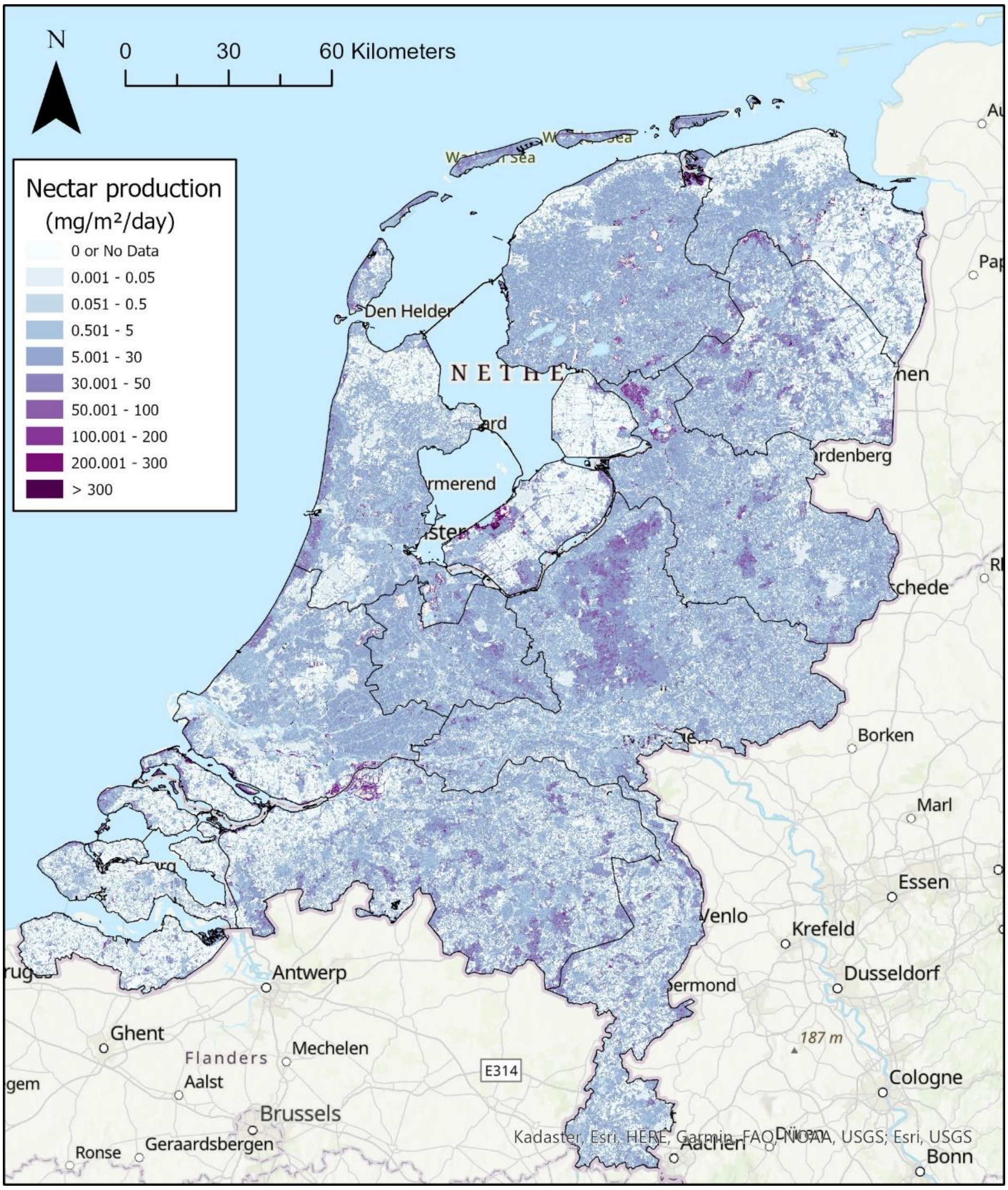

Figure 22: Nectar sugar production without intensive agricultural areas across the Netherlands in 2022, based on method 3+4. This figure is presented as an addition to Figure 19 to highlight the role that intensive agriculture plays in the availability of nectar.

3.2 Comparison with pollinators presence

The comparison between the supply side -nectar sugar production- and the demand side -bee diversity- leads to the identification of hotspots of pollinators potentially lacking food availability, or hotspots of food availability where few pollinators are expected to be present. *Figure 23* illustrates the distribution of both classified variables separately, while *Figure 24* depicts their combination.

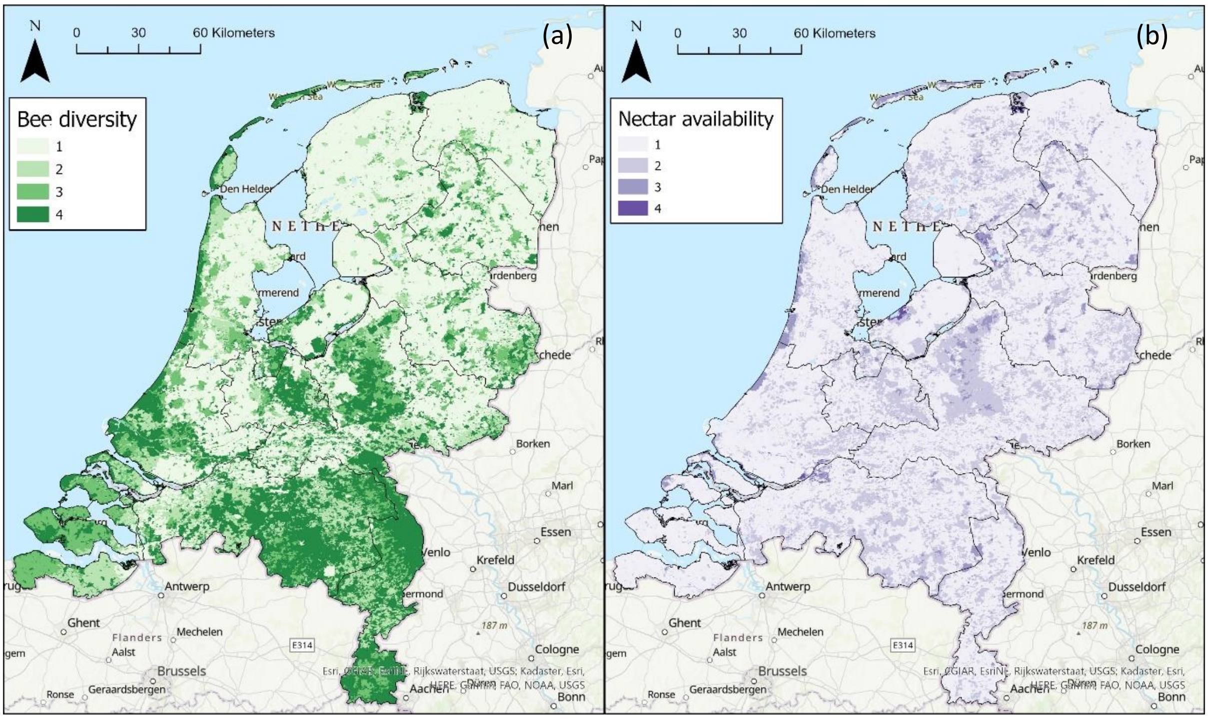

Figure 23: Distribution of the bee diversity (a) and nectar sugar production of method 3+4 (b) across the Netherlands in 2022 for comparison of floral resources supply and demand. The classifications 1-4 can be found in Table 3.

One can observe the bee diversity pattern, with high diversity in the Southern provinces, the entire coastal area and the natural areas more North such as Veluwe, Oostvaardersplassen, or Kalenberg. Among those, the dunes coastal areas and the natural areas are the only ones presenting a high nectar production and therefore potentially matching the requirements of such area. Southern provinces (Limburg, North Brabant, Zeeland) appear with a particularly low nectar production compared to the bee diversity observed, except from some patches of natural areas. This high bee diversity in the South contrasts with the North due to temperature ranges among other factors. The North of the Netherlands presents less bee diversity for a similar nectar production.

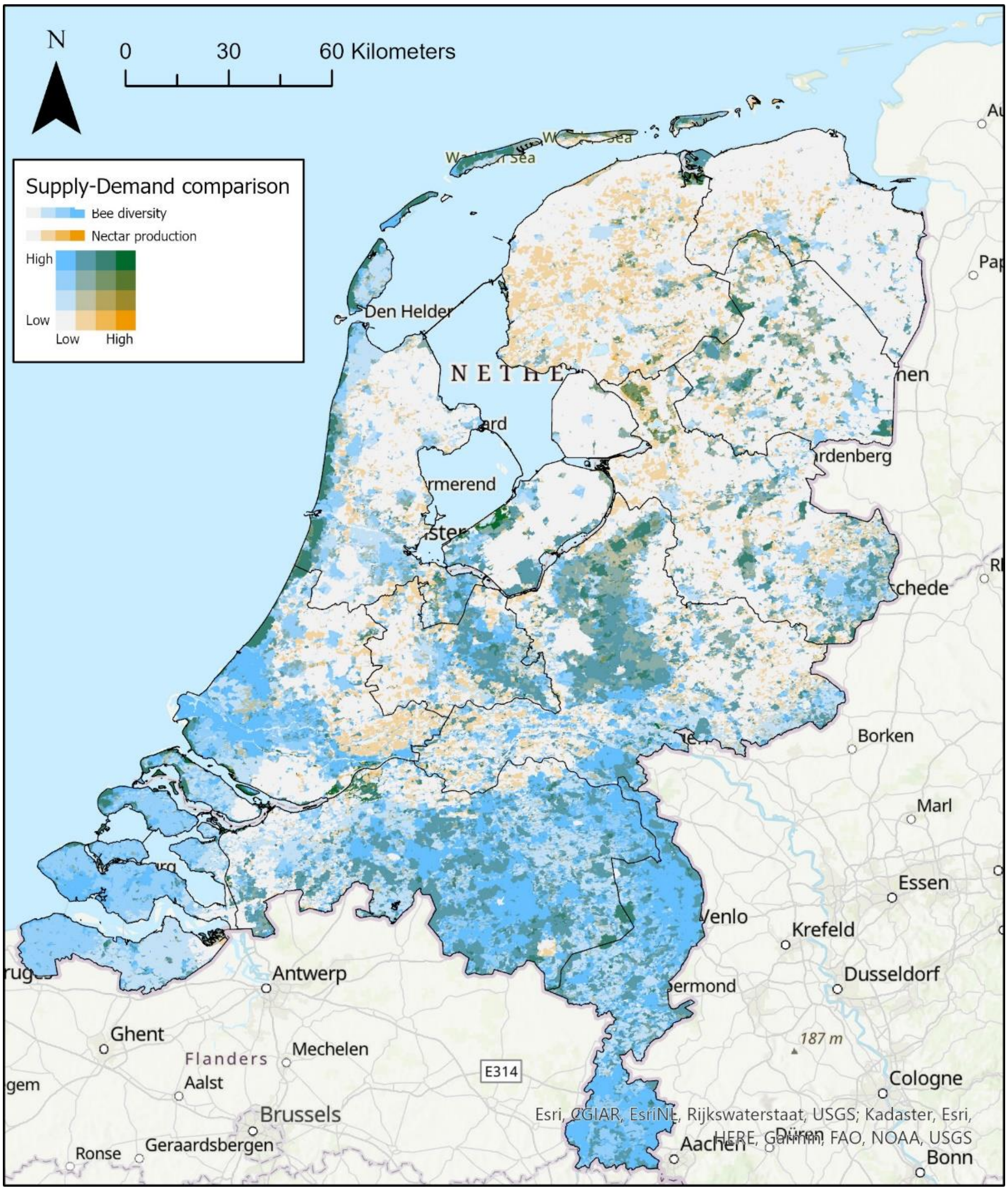

Figure 24: Comparison of nectar sugar production and bee diversity in the Netherlands in 2022. The map provides an overview of the relationship between nectar sugar production and bee diversity, highlighting areas with varying levels of supply and demand of floral resources. The colour scheme represents the following: blue indicates high bee diversity alone, orange represents high nectar production alone, and shades of green indicate areas where both variables coexist favourably. For a detailed information of the classification of bee diversity and nectar sugar production into four categories, please refer to Table 3.

This analysis reveals that a significant part of the Netherlands exhibits a high bee diversity but a low nectar production. This finding highlights the critical nature of the situation, suggesting that food availability may be a factor limiting the population growth of pollinators in many parts of the country. Specifically, the provinces of Flevoland, Groningen and the western region of North Brabant appear to be particularly deficient in terms of both bee diversity and nectar production. It should be noted that the diversity here studied differs from the abundance of pollinators, which might draw different conclusions for some situations. Additionally, it is essential to recognise that the outcome of the analysis are influenced by the chosen classification system.

4.Discussion

4.1 Scientific implications

This study demonstrates that land uses differ substantially in the floral resources they produce, which can help inform how areas could be better designed and managed to allow for pollinators to benefit from it and to be able to live in broader areas as well as connecting multiple living areas. It also presents a framework of the best way -as of today- to reach a model-based floral resource quantification in the Netherlands, and highlights the major gaps and inconsistencies of the current literature. This provides insights into the most pressing items to research in order to obtain a more reliable quantification. This model-based quantification of pollen and nectar production is a novelty, building on a first model-based study performed by Baldock et al. (2019). This study focused on four British cities and investigated floral and pollinator abundance. The maps resulting from the study stand as examples of what could be achieve, and allow to draw first conclusions on the availability of floral resources for pollinators across the Netherlands. Some information for quantifying floral resources in natural areas is present, but limited species are represented and the combination with modelling to represent its distribution is scarcer. This study builds on this, adds more details in the supply of floral resources for urban areas, and gives insights in the possibilities for agricultural areas.

4.2 Method 1

The first method based on plant species richness informs on how attractive to pollinators an area is compared to another. This also gives information on pollinators as flower diversity is related to bee diversity and abundance (Fründ et al., 2010). However as mentioned above, there is no quantification of production in this method and it is therefore only useful in the identification of hotspots of attractive areas versus areas that need better management. Moreover, only the 50 plants most visited by pollinators were assessed here. This number of species should be extended to all nectar/pollen producing plants to reach a more reliable analysis **[1]**.

Weighting choice

The choice of the proxy used for the abundance of pollen and nectar is critical to the message that the results convey. In this research, the amount of bee species visiting plant species, and the diversity of plants were used. Other proxies have been considered, such as the one-to-five ranking regarding attractiveness to honey bee species by Koster (1993), or other pollen relative values. The list of bee species visiting made by Fijen & Kleijn has been decided for its quantification approach. As opposed to the ranges 1-5, this quantification allows to not overlook the difference between a high 3 or a low 3. The use of species richness as an attractiveness index is debatable and Hegland & Boeke (2006) assessed that 'blossom density was a better predictor of flower visitor richness and activity than was plant species richness'. Further investigation of the potential of using blossom density or direct production values could therefore be analysed to obtain a more accurate attractiveness index **[2]**.

SDM limitations

This method builds on the predicted presence of plant species through SDM maps. It should be kept in mind that such modelling has multiple limitations which were presented by Mateo et al. (2011). For instance it assumes an equilibrium between the considered species and the environmental conditions (Araújo & Pearson, 2005), or the absence of the time and spatial component in the modelling process. This means that the presence is assessed in a certain point regardless of the result of this assessment in the neighbouring points, which can create contradictions in the prediction of a species presence where e.g. climatic barriers isolate some areas. However, it remains a valuable method to study living areas of species, and allows for combination with other tools for conservation plans of such species. Additionally, it should be noted that a small area of data is absent in the SDM maps and the bee diversity map created by Naturalis. This area is located in the South East of North Brabant. This discrepancy may be attributed to potential data sources issues, which might have been resolved or improved since the creation of these maps.

4.3 Methods 2 and 3

Plant communities

The use of plant communities in methods 2 and 3 with SynBioSys, allowed to identify a potential species composition for an environment, based on a list of species, along with their percentage cover and percentage presence in this community. In that sense, they are very valuable to define an environment and link it to direct pollen and nectar values (as used in this study) or other species-specific parameters. However, plant communities usually provide an idealistic view of the species actually present in an area. Through the percentage of presence, it is easy to picture a very rich environment, while it might be covered by very few species. It also does not account well for degraded areas, therefore usually ending up with an optimal composition of species present. This limitation to the use of plant communities was reduced as much as possible through using the percentage presence as a factor in the calculation but should direct the results to be viewed more as a potential of floral resources in that area rather than what could actually be measured. In the case of the best management possible of the area, the results show what the floral resources stocks could look like. Additionally, it is important to acknowledge that method 2 and 3 used different syntaxonomy classification, both provided by SynBioSys. The first classification provided the plant community distribution while the second classification relied on the BWK information. This discrepancy in classification methods reduces the comparability between the two methods, but it was necessary in order to carry out the respective analyses.

SynBioSys

SynBioSys not only was used for its plant communities data, but also for the distribution of these plant communities through the Landelijke Vegetatie Database (LVD). It compiles raster data on where the plant communities appear. SynBioSys allows to adjust the use of LVD or of the Atlas van Plantengemeenschappen for this distribution as well as to adjust the time period of the observations to consider. In this case, LVD and the whole period (meaning all the observations ever compiled) were selected. However the choice of a database or another, and of a period or another directly influences the distribution of the plant communities and therefore the distribution of pollen and nectar used as results. The latest versions of SynBioSys also include urban areas based on the 'spontaneously growing' plant communities (as opposed to artificial) and therefore human-induced planting is not considered (Roos, personal communication).

Data availability

The results obtained in methods 2 and 3 are based on both databases of FloRes and SynBioSys. This dependency requires extra attention on the validity of those results. The databases have been identified as the most accurate ones available for the quantification intended (especially because of the value of the floral density). However, further research should be done to validate, or specify these results in e.g. different environments or conditions. Furthermore, FloRes only covers about 70 species, 36 of which were considered for the study (and only 29 for pollen). This is a limited sample compared to the amount of species for which data is available in SynBioSys. This difference causes a biased set of results towards these plant species, and the availability of data for the species present in FloRes should be extended to all plant species present in SynBioSys to obtain a more reliable model. As an example, the second nectar high availability period in autumn is highly influenced by the flowering of *Calluna Vulgaris* which has a very high nectar sugar production. The pollen production of *Calluna Vulgaris* was not available in FloRes and a similar peak therefore might be observed for pollen if the data became available. Additionally, the data obtained in FloRes also was obtained at peak flowering further increasing the overvaluation of the quantification for these two methods. Further research for validating and extending FloRes would be advised, as the number of species is very limited and most of the ones sampled only contain two sample sites. This creates an understatement of the quantification, balancing with the overstatement of plant communities. It is hard to tell which overtakes the other, but it could be overall overstated as the results of this study are slightly higher than the results of Tew et al. (2021) (see *Section 4.5*). Validation could be performed using other studies quantifying nectar sugar production for different taxa (e.g. Baude et al., 2016, Hicks et al., 2016) **[3]**.

Flowering months

The flowering periods of the species considered coming from FloRes and Waarneming.nl also show limitations. Waarneming exhibits a bias towards the months of spring where citizens usually go out more than in winter to observe and identify species. The flowering months of FloRes are also based on only two sample sites, suggesting unreliable data considering that the phenology and quantities of plants flowering varies over years (Flo et al., 2018). This data was selected to provide consistent use of the same database, given the high value that FloRes was delivering for the floral unit density and nectar and pollen production values but further work could extend on the flowering months of the species considered **[4]**.

Average availability

Both methods deliver similar trends and results under most angles, except when looking at monthly average availability. The average pollen availability follows a somewhat similar trend except from a major gap in the availability for the month of May in method 3 while it is the highest availability month in method 2. Nectar availability also shows a similar gap for the month of May but instead exhibits highest availability in late summer and specifically September. The may gap could potentially be induced from a higher presence of Salix species in the second syntaxonomy classification which have a high production of nectar and pollen but only flower in March and April. The difference of one order of magnitude witnessed between both methods in absolute availability values is expected to be partly due to the non-inclusion of urban areas in method 3, for which a value of 0 was given.

Comparison to literature

It is expected that the low coverage in terms of species considered might be reducing the food availability of a diverse, natural area like Veluwe more than of species-poor areas. Based on the amount of species expected, it is likely that relatively speaking, the diverse area has a lower accuracy than the non-diverse one. It is also possible that for some areas it translates into the opposite. Either way, this should be kept in mind when using the results of the study to identify areas as low floral resources availability. Interestingly, both methods show different timings in peak flowering, with the peak nectar production ending earlier in method 3 than in method 2. Timberlake et al. (2019) studied nectar supply on a British farm level, and identified a ‘June gap’ between high nectar availability in May and July. These result show a similar gap between May and June (especially method 2), and on average in May (method 3) but not in July. When focusing on farmland data, the plant communities associated with the ‘Field’ land use show a peak production in the months of June to September, therefore not fitting the results of Timberlake et al. (2019), who assessed a ‘June gap’ in the availability of floral resources. This could be due to the low amount of plant species considered.

Biological assumption

The association of land use data from LGN with plant communities from different ecological areas from BWK is expected to be ecologically inaccurate. This association was the most precise found but it remains a critical assumption. The combination of such data with soil type data might be a way to improve the reliability of this association. Other studies also investigate different habitat types to quantify their pollen/nectar production (e.g. Baude et al., 2016) **[5]**. This study remains very limited regarding agricultural and urban areas, which represent a significant share of the Netherlands. The

BWK used for identifying habitat types does not provide any plant community for urban areas and they are therefore excluded of this method. Additionally except from grasslands, all crop types were categorised under the same land use 'Field'. This does not account for any difference in agriculture type, or even crop type for which data is available in the BRP gewasparcelen database. The difference between *Figure 20* and *Figure 22* shows the potential extent of the role of intensive agriculture in reducing the availability of nectar for pollinators. The lacking information is the production of nectar and pollen of the different crop types along the months. Conducting research on the production of the different crop types and implementing it in the model combined with data on more plant species holds high potential for improving the accuracy of the results of method 3. Additionally, a more precise definition of intensive agriculture could be investigated to provide better insights in what could be achieved by transitioning to sustainable agriculture **[6]**.

4.4 Method 4

Value added

Method 4 provides novelty in model-based floral resource quantifications through the use of urban land use classification and sampling of Tew et al. (2021). The study it builds on (Baldock et al., 2019) used this classification to map the distribution of floral abundance and other characteristics but not to combine nectar and pollen production volumes with a distribution of these land use classes. Tew et al. (2021) sampled this nectar sugar production per land use in four British cities, and the results of this method therefore are really dependent on the assumption that the floral composition of urban classes are similar in the UK and in the Netherlands as similar data was not found in the Netherlands. A similar study for Dutch cities would allow to validate the results and confirm the assumption **[7]**. Very recently (early June 2023), Tew et al. (2023) sampled nectar production at the species level of plants in urban areas, including many non-native plants (majority of the plants in urban areas). This brings potential for quantifying nectar production in urban areas directly at the species level, allowing for a better use of the British data in the Netherlands **[8]**.

Classification assumptions

The results of the urban land use classes method (see *Section 2.2.4*) are also very dependent on the way of classifying the urban classes. Care was taken to fit as much as possible to the way the authors of the data classified themselves the land use classes, however depending on the availability of the data, some were not fully accurate. First of all regarding the way to define urban areas, the 'bebouwde kom' from the TOP10NL 'plaats_vlak' layer used for this definition has inconsistencies that should be improved for further study (e.g. the municipality of Gouda is missing). Regarding pavements, the layer was created by selecting the 'paved' roads but after checking on known areas, a lot of roads were defined as paved despite being made of asphalte. The pavements are defined by Baldock et al. (2019) as the public walkways, therefore deriving from this classification of paved roads. However for Dutch cities the separation between a paved road and a public walkway is less clear than in the UK (because of the place of bikes allowing for most city centre roads to be used easily by bike/pedestrian). Being able to make a more precise separation between (asphalte or paved) roads and sideways would allow to get a more accurate result on the pavements **[9]**.

Greenness of the gardens

Regarding private gardens, the use of residential parcels from the cadastre make a reliable dataset. However here the areas of the parcels that are not a building was selected as a garden whereas some parts might be pathways, terraces or other types of land use that are not 'green'. It was not specified whether this was taken into account by Tew et al. (2021), but attention to a better classification of the green part of the urban private gardens could make a more reliable dataset. A student of the MSc Industrial Ecology Huub Diepens is in the process of writing his MSc Thesis on classifying the greenness of the gardens. His work could be combined with this research to obtain more accurate gardens **[9]**.

This is all the more important as Tew et al. (2021) conclude their study by defining the residential gardens as the key land use driving nectar sugar production in urban areas.

Other green spaces

Lastly, the other green spaces data is made from the Groenkaart (see *Section 2.2.4*): a raster map of 10m x 10m. It is expected that some precision is lost in this layer based on both its definition and resolution compared to the 5m x 5m data (or 1m x 1m) of the other land uses (later aggregated to 100m x 100m). More detailed data sources should be used for a more accurate layer **[9]**. For the mapping of one city, it could be interesting to use the definition of landscape elements for the other green spaces. On the country level, this seems too much 'hard-mapping' and the Groenkaart appeared as the most accessible and accurate data source.

4.5 Method 3+4

The final nectar sugar production is evenly distributed among the Netherlands, with a similar production of about 5-15 mg/m²/day for urban, and non-urban areas and an overall average of 6.3 mg/m²/day (ArcGIS Pro statistics). This aligns with the results of Tew et al. (2021), who assessed a similar nectar production in urban, natural and farmland areas of about 2-8 mg/m²/day (*Figure 25, (A)*). The natural reserves in this study however appear as slightly higher than the production for urban areas, which could be explained by the over-evaluation of plant communities.

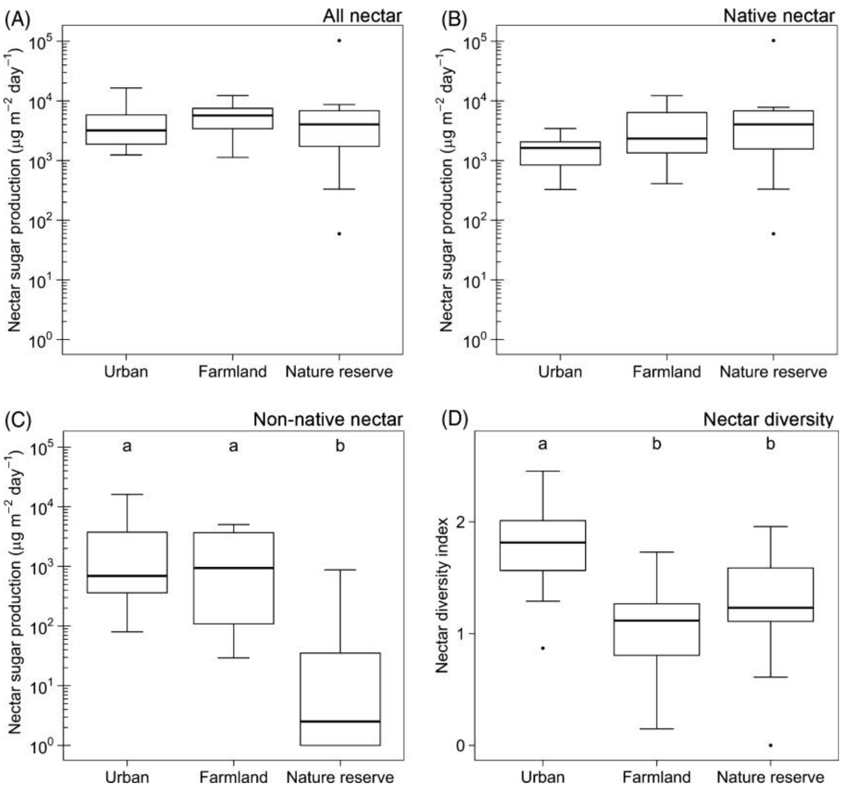

Figure 25: Box and whisker plots of the mass (A–C) and diversity (D) of the nectar supply in urban, farmland and nature reserve landscapes. Daily nectar sugar production per square metre was calculated by dividing total nectar sugar production per sampling site by 100 (as 25 m2 of land was sampled on four occasions). Data were subsequently transformed (log10(x + 1)) for visualisation on a logarithmic y-axis and are shown for (A) all plant taxa, (B) native plant taxa and (C) non-native plant taxa. Nectar diversity index (Shannon index of nectar sources per sampling site) is shown for all taxa (D). Significantly different landscape types are indicated by different letters (Tukey multiple comparison tests). Boxes show the median, 25th and 75th percentiles; the whiskers extend to 1.5 × the interquartile range; and all outliers are shown. Journal of Ecology, Volume: 109, Issue: 4, Pages: 1747-1757, First published: 26 January 2021, DOI: (10.1111/1365-2745.13598). No changes were made from the original content. License: http://creativecommons.org/licenses/by/4.0/

Urban definitions

For this study, methods 3 and 4 have slightly different 'urban' definitions for which two things should be considered: it induces some non-urban areas of method 4 to still have a null production of nectar in the combination because they are considered as urban in method 3. In addition, with the aggregation to 100m x 100m in method 4, some cells have a very low nectar production (less than 0.1 mg/m²/day) to a point where they could be considered non-urban and some of these areas might have data with method 3. However with the priority given to the urban values of method 4 the close-to-zero production cells are given priority. These slightly different definitions should be better aligned for further analyses **[10]**. While the definitions of urban areas remain different, a threshold below which the area of method 4 is considered non-urban could be introduced for further development. The monthly availability of data is essential for analysing the phenological balance between supply and demand, vital for the conservation of pollinators (Harris et al., 2023), thus efforts should be made to obtain monthly data for urban areas **[8]**.

4.6 Comparison of methods

The five methods (four methods and 3+4) yield into different end results and all deliver valuable information towards answering the research question and reaching a floral resource quantification. *Table 4* compiles the main criteria required for such quantification and whether the different methods complete them. This allows, based on what seems most important to select which method is the most appropriate to a study. Specifically, the resolution of data obtained in the different methods vary greatly. It is interesting to mention that the data used for method 4 could allow to obtain a resolution of 10m x 10m but it was decided to work with 100m x 100m for limiting the size of datasets when looking at the national scale, which also could reduce the data uncertainty and extent of the modelling issues (e.g. horizontal lines obtained when turned into rasters, see *Section 2.2.4*). The difficulty was qualitatively assessed based on experience and number of steps repeated for the analysis.

Table 4: Comparison of the different methods implemented in multiple criteria. This table provides a comprehensive comparison of different methods used for floral resource quantification, evaluated across various criteria including the inclusion of a quantification of the production, rural areas, urban areas or monthly information, as well as the resolution obtained and qualitatively assessed difficulty of implementation.

CRITERIA	METHOD 1	METHOD 2	METHOD 3	METHOD 4	METHOD 3+4
Production quantification		X	X	X	X
Resolution	100m x 100m	1km x 1km	5m x 5m	100m x 100m	100m x 100m
Rural area	X	X	X		X
Urban area	X	X		X	X
Monthly information	X	X	X		X
Difficulty	▌	▌▌▌	▌▌	▌▌▌▌	▌▌▌▌

If the first two methods perform well in integrating all areas and monthly data, the low resolution or absence of abundance data make them less accurate. Method 3 was identified by Arjen de Groot (personal communication) as an improvement of method 2 specifically through the finer resolution obtained. It is important to mention that the table does not highlight the advantages of method 4 of precisely quantifying the nectar for urban areas. The last two methods, focusing each on different land use types allow for more accurate quantification and their combination into Method 3+4 (see *Section 3.1.5*) appears as the most accurate quantification among all used.

4.7 Demand side

Due to time constraints, the quantification of the food resources demand, established on the quantification of pollinators themselves has been put aside to focus solely on the distribution of food resources availability. The demand side was then included through the bee diversity variable.

Interspecific interactions

In the entire study, the interaction between specific plant and pollinator species has not been used. Through the focus on the floral resource availability side, implementing such interaction seemed inadequate to the aim of providing general information that could apply for all different kinds of demand. The data was limited enough in this general way, reducing the availability through focusing on the more detailed interactions would have reduced it further. When overlaying with the pollinator presence, this very general approach was used, through using bee diversity as the 'demand' side indicator. However depending on the focus of another study, all bee species do not need to be included: for conservation studies, a focus on the redlist species would be of higher use, while for ecosystem services studies the focus could be set on the biggest crop-pollinating species **[11]**.

Key message

Comparing the supply side to the demand one regarding floral resources brings insights into areas of attention where low food availability is associated with high predicted presence. The critical areas could imply that food is the limiting factor for pollinators to actually thrive in such area, but care should be taken with such conclusions as other factors are in play, e.g. the availability of nesting sites for pollinators. In all cases, it highlights areas that appear as critical and that should be investigated further **[12]**. This study was intended to be performed for the single year 2022, to explore the most up to date datasets. The downside of such perspective is that the availability of data made it hard to fit to one year, as some data was yet not available up to this year. In such case, the most recent available data was selected (e.g. 2021 for LGN). The use of up to date data could allow for a more accurate picture of the floral resources availability. The combination with a multi-year analysis could allow to analyse the trends in floral resource availability and identify shrinking areas and improving areas, especially considering that Flo et al. (2018) assessed variability in the pollen and nectar availability over years. This could be performed by using land use data from different years and specifically by including the changes in crop grown in agricultural areas **[13]**.

The floral resource availability results of this study should be combined with another study focused on more detailed floral resources demand **[14]**. This was identified by Dicks et al. (2015) as a key research agenda and still should be investigated. This other study could use SDM maps with the recommendation that flower richness is used as a biotic variable for generalist species and genus-level data is used for specialist species (Moens et al., 2022). It could also look into the requirements for all pollinator species (bees, hoverflies, etc). The bee diversity map also builds on a set of parameters which include food availability through expert judgement by Koos Biesmeijer, the results of this study could therefore also be used to directly quantify the food availability to (hopefully) improve the accuracy of the bee diversity map **[15]**.

4.8 Societal relevance

This study provides a framework of the way to reach a national monthly quantification of floral resources in order to help the conservation of pollinator species and food security. Climate-change related threats to pollinators translate in the possibility of observing higher national bee diversity but lower EU diversity (Reemer et al., 2012). This potential increase in diversity comes with a high turnover of species expected to happen with species present in countries south of the Netherlands (e.g. Belgium, France) seeking similar climatic conditions moving North. If the absence of pollinating insects does not appear as a threat in the near future in the Netherlands, it is critical on an EU-perspective to work towards helping pollinators maintain their presence in the area while allowing new species to thrive. For the Netherlands, the turnover expected in response to climate and land use change is highly unstable: all current interspecific interaction will need to be recreated similar to Finland, in which only 7% of the interactions remain compared to the early 20th century (Zoller et al., 2023). Thus, this study delivers both a first step towards the national quantification but also a framework of the pathway that should be taken by other EU countries to obtain better awareness on the distribution and consequently on the most critical areas to take action on.

Nectar quality

Through performing the quantification for nectar sugar content, this study delivers key information not only on nectar quantity, but also its quality and therefore goes one step further in the value of an area to allow pollinators to thrive or not. This is often overlooked and is a critical factor to consider when implementing management practices as increasing the quantity of flowering plants is likely not sufficient to ensure bees maintenance (Pamminger et al., 2019). The information on the quality of pollen (protein content) was not sufficient to investigate to a similar extent the quality of nectar and pollen.

Practical implications

The findings of this study have practical applications in decision making for municipalities, provinces, and agricultural farms in enhancing floral resources and promoting pollinator-friendly practices. Municipalities can use the conclusions to identify areas that require focused attention in their urban planning management plans, aiming to increase floral resources. Similarly, on a larger scale, provinces can direct their investments towards managing specific areas to support pollinator populations. Agricultural farms can incorporate pollinator-friendly practices into their operations, aligning with the study's recommendations. Research institutes and universities can also build on this research to effectively tackle the limitations and update the model with newly available information. Government and various organisations could use this study to build a similar model allowing to perform scenario analysis and identify the response to specific changes regarding floral resources availability for pollinators for further informing the aforementioned decisions.

4.9 Recommendations for further research

To summarise, I recommend the following:

[1] Extend the number of plant species included in the calculation for method 1.

[2] Improvement of the attractiveness index of method 1 by replacing the weighting by a list of production values. Investigation of the potential use of blossom density instead of flower richness.

[3] Validate and extend the data of both SynBioSys and FloRes databases. Specifically, increase the number of species covered in FloRes and number of sample sites, while exploring different environments and conditions.

[4] Validation of the flowering months of the species considered in FloRes.

[5] Explore the use of soil type data to improve the reliability of the association plant community-habitat type. Explore other datasets than the 'Revisie vegetatie van Nederlands'.

[6] Conduct research on the **production of the different crop types** and implement it in the model to more accurately model the availability in agricultural areas.

[7] Validate the assumption of **similar urban land uses floral composition** in the UK and the Netherlands.

[8] Explore the **use of the Tew et al. (2023) dataset** to extend the modelling of food availability in urban areas and include flowering months for monthly data.

[9] Make a more precise separation between (asphalte or paved) roads and sideways and validate the different land uses of method 4. Explore the inclusion of the MSc thesis of Huub Diepens to accurately model the private gardens and investigate other datasets for the 'other green spaces' layer.

[10] Align the definitions of urban areas for the different land uses (urban, natural and agricultural).

[11] Depending on the study, analyse what species should be included, and reflect on the addition of interspecific interaction.

[12] Use the comparison between floral resources availability and demand as a highlight of areas to investigate further to identify if food is indeed the limiting factor.

[13] Use **updated data that fits the year of study**, and investigate multi-year trends in floral resources availability. This includes the use of different land use data and taking into account the changes in crop grown in agricultural areas.

[14] Extended research on the **floral resources demand** in the Netherlands should be performed.

[15] Investigation of the use of the results for replacing the expert opinion of food availabity provided by Koos Biesmeijer in the Bee diversity map (RIVM, 2017).

On a more general note, I recommend further research on the improvements previously mentioned, as well as the combination with further research on the floral resource demand and the quantification of pollinators. In priority, I recommend research on floral resources trait data and the combination of different methods each focusing in-depth on a specific land use type (urban, natural or agricultural). This goes with further research on phenological synchrony of the supply and demand in floral resources. Finally, the use of remote sensing and airborne imagery could be particularly promising for accurate resource quantification in the coming years. Drones and satellites become increasingly accessible and provide high potential for capturing richness and abundance of floral resources through e.g. RGB images (Gonzales et al., 2022). At landscape level, mapping flowers could be performed at fine resolution (a few centimeters) with an accuracy of about 95% (Barnsley et al., 2022).

5.Conclusion

As a reminder, this study aimed at answering the following research questions:

1. Which quantification methods can be used to reach the floral resource distribution and how do they compare?

2.How are floral resources (nectar and pollen) spatially distributed over the Netherlands per month of the year 2022? How do the different methods perform?

3.How does pollinators' richness compare to floral resources over the Netherlands in the year 2022?

1.This study compared different quantification methods to assess the distribution of floral resources in the Netherlands. Through the evaluation of these methods, insights into their strengths and limitations were gained. Their suitability for future research and practical applications support the use of methods focusing on specific land use and combining them together to gain reliability. These methods however require further research for increasing the data availability and improve the reliability.

2. The findings revealed that floral resources availability showed temporal variation, with peak production observed in the months of March, April and May, while a second -but lower- peak of nectar production was observed in autumn. The spatial distribution varied across the country, with resource availability evenly distributed: some natural areas showing similar production of nectar to urban areas while other natural areas had slightly higher average nectar production. The distribution of hotspots was similar in most methods, but it resulted into values varying over an order of magnitude.

3. The investigation of the relationship between pollinators' richness and floral resources revealed that the South of the Netherlands exhibited a deficit in food supply relative to the richness of bee species predicted in that region. It emphasises the importance of ensuring an adequate supply of floral resources to support diverse pollinator communities. Natural areas were found to have a better balance between the supply and demand of floral resources. This should be further investigated to compare food availability with food demand.

These findings have important implications for decision-making in land management for pollinator conservation and the stability of the ecosystem services they provide. Additionally, the study identified the current missing information in literature for more accurate quantification: the number of plant species considered were quite limited and agricultural areas specifically were lacking required data. This study serves as a foundational step towards a much bigger step of accurately quantifying floral resources supply and demand in order to provide support to decision-makers for the conservation of pollinator species. It also serves as a methodology guide for future research in other countries.

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Appendix

Appendix 1: 50 most visited plant species.

This appendix presents the list of the 50 plant species most visited by bees and the number of bee visiting associated. This list is depicted in *Table 5* and has been made by Thijs Fijen (WUR). This list is only available in an unpublished document on the WUR website and was obtained thanks to Arjen de Groot.

Table 5: List of the 50 most visited species and the number of species visiting them.

Aantal soorten bijen per plantensoort.

	Plantensoort	Bijensoorten
1	Taraxacum congl.	107
2	Cirsium arvense	98
3	Jasione montana	71
4	Lotus corniculatus	71
5	Trifolium repens	67
6	Jacobaea vulgaris	65
7	Heracleum sphondylium	63
8	Calluna vulgaris	62
9	Prunus spinosa	62
10	Rubus fruticosus	55
11	Echium vulgare	54
12	Tanacetum vulgare	54
13	Glechoma hederacea	52
14	Daucus carota	51
15	Frangula alnus	50
16	Vaccinium myrtillus	50
17	Trifolium pratense	49
18	Centaurea jacea	48
19	Hieracium pilosella	48
20	Salix caprea	48
21	Potentilla erecta	45
22	Reseda lutea	45
23	Chamaenerion angustifolium	44
24	Salix repens	44
25	Solidago canadensis	44
26	Crepis capillaris	43
27	Aegopodium podagraria	41
28	Lamium album	40
29	Brassica napus	39
30	Achillea millefolium	38
31	Crepis biennis	36
32	Cirsium palustre	35
33	Campanula rotundifolia	34
34	Pulicaria dysenterica	34
35	Knautia arvensis	33
36	Tussilago farfara	33
37	Erica tetralix	32
38	Leontodon autumnalis	31
39	Bellis perennis	30
40	Cirsium vulgare	30
41	Hypochaeris radicata	29
42	Potentilla reptans	28
43	Rhamnus frangula	28
44	Salix cinerea	28
45	Bryonia dioica	27
46	Sisymbrium chrysanthum	27
47	Solidago gigantea	27
48	Ficaria verna	26
49	Symphytum officinale	25
50	Brassica nigra	24

Appendix 2 : Detailed methodologies of methods.

In this appendix are listed the five methods (four methods and 3+4) with additional details on how they were performed. It includes more detailed workflow diagrams, screenshots and additional explanations.

Appendix 2.1: Detailed methodology of method 1.

The SDM maps were obtained from the research group Biodiversity & Society of Naturalis. The weighting was compiled in a table along with the flowering months of each species from FloRes and Waarneming (*Table 6*). The full table can be found in Supplementary data 1: Weighting table. Through filtering this allowed to quickly obtain the list of species to consider per month and their weight. This list was then manually added as a sum to raster calculator month by month (see *Section 2.2.1*) to obtain 12 raster maps.

Table 6: Table of 14 of the top 50 plant species in number of bee species visiting.

Number	Plant_species	Bee_species_visiting	Weighing_factor	Flowering_start	Flowering_end	Source of flowering	Counted?
1	Taraxacum congl.	107	4.458	Apr	Oct	FloRes	Yes
2	Cirsium arvense	98	4.083	Jul	Sep	FloRes	Yes
3	Jasione montana	71	2.958	Jul	Oct	Waarneming	Yes
4	Lotus corniculatus	71	2.958	May	Sep	FloRes	Yes
5	Trifolium repens	67	2.792	May	Sep	FloRes	Yes
6	Jacobaea vulgaris	65	2.708	Jun	Sep	FloRes	Yes
7	Heracleum sphondylium	63	2.625	Jun	Sep	FloRes	Yes
8	Calluna vulgaris	62	2.583	Aug	Oct	FloRes	Yes
9	Prunus spinosa	62	2.583	Mar	May	FloRes	Yes
10	Rubus fruticosus	55	2.292	May	Aug	FloRes	Yes
11	Echium vulgare	54	2.25	May	Aug	FloRes	Yes
20	Salix caprea	48	2	Mar	Apr	FloRes	Yes
13	Glechoma hederacea	52	2.167	Apr	Jun	FloRes	Missing SDM
14	Daucus carota	51	2.125	Jun	Aug	FloRes	Yes

Appendix 2.2: Detailed methodology of method 2.

The detailed flowchart used for method 2 can be found in *Figure 26*. The data from SynBioSys was compiled in an Excel File to allow for easy sorting by flowering month and identify which plant species to include (*Table 7).* The full dataset is available in Supplementary data 2: Top50_FloRes_data. FloRes provides information on the days of the flowering start and end, which were turned into months. Most of the time the day was the first/last day of a month, and when not (highlighted in orange), the month it was part of was selected as the starting/ending month. Nectar sugar content and pollen were turned into per square meter values through the flower density. When no pollen data was available, a value of zero was attributed.

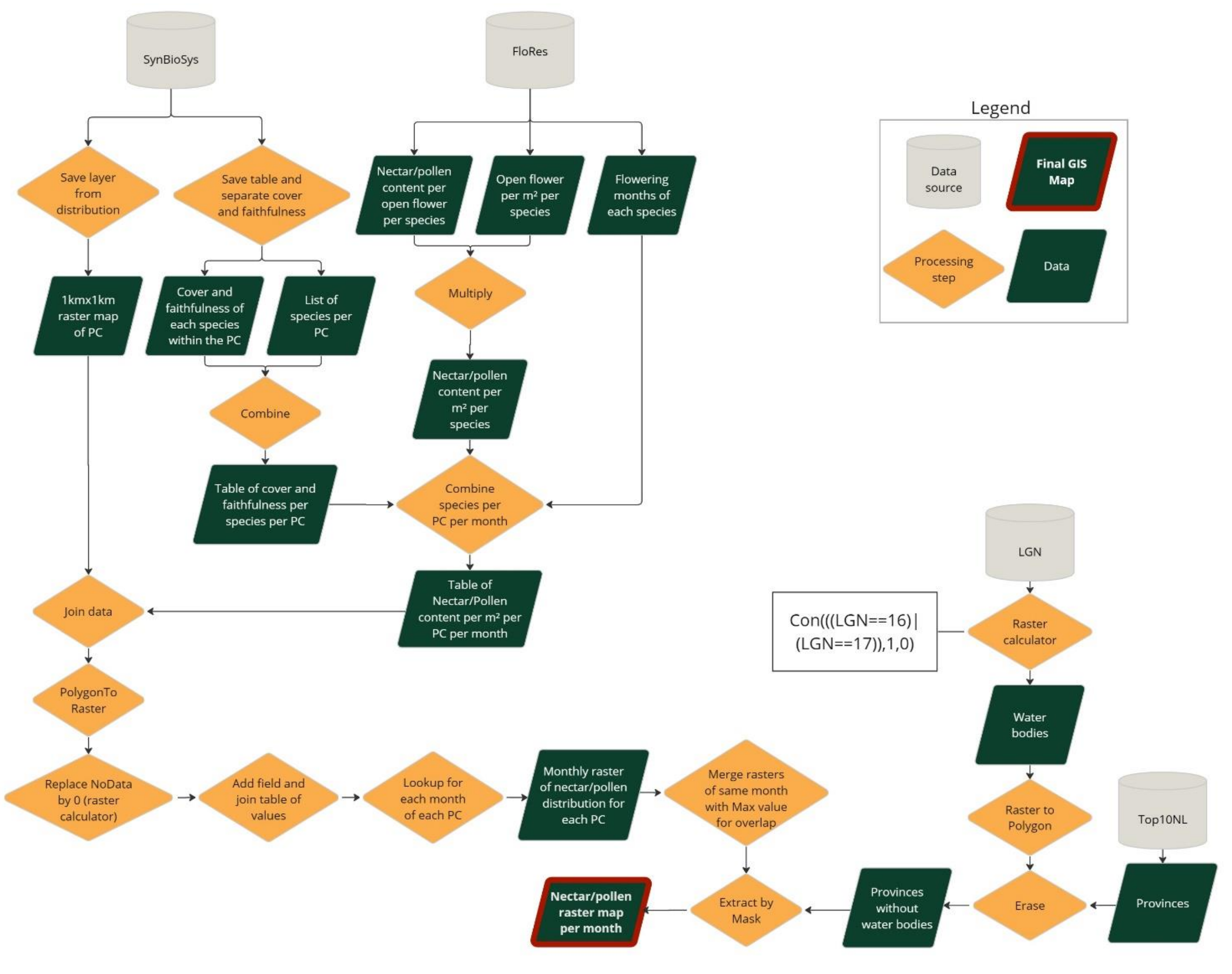

Figure 26: Detailed workflow diagram of method 2.

Table 7: Table compiling the data obtained from FloRes.

1	species	flowering_start	flowering_end	flowers_m2	nectar_ml	nectar_sugar_content_mg	pollen_mg	nectar_sugar_content_m^2	pollen_mg_m^2
2	Achillea millefolium	Jun	Aug	25041.34107	6.93E-05	0.032600422	0.17449896	816.3582894	4369.687985
3	Bellis perennis	Jan	Dec	303.7035789	0.00012358	0.058164574	0.166767526	17.6647893	50.64789453
4	Brassica napus	May	Jul	1125.12	0.007459838	5.229702799	0.78174175	5884.043214	879.5532778
5	Brassica spec (nigra, olerac	May	Aug	124.182	0.001308007	0.9885	1.15	122.753907	142.8093
6	Calluna spec (vulgaris)	Aug	Oct	5815.06	NA	0.19588	NA	1139.053953	0
7	Campanula spec (rotundifo	Jun	Oct	329.14	NA	0.29018	NA	95.5098452	0
8	Centaurea spec (jacea, mor	Jun	Oct	27.39901463	0.032444667	8.001190144	10.9115454	219.2247258	298.9655921
9	Cirsium arvense	Jul	Sep	65.52482517	NA	4.574308702	0.06002336	299.730778	3.933020202
10	Cirsium palustre	Jul	Sep	240.4929401	0.000639333	12.279024	5.053333	2953.018584	1215.290911
11	Cirsium vulgare	Jun	Oct	42.3657377	0.001824667	10.15286557	3.066667	430.1336396	129.9216098
12	Crepis biennis	May	Sep	440.3428571	0.000214642	0.101024	0.627631557	44.4851968	276.373073
13	Crepis capillaris	Jun	Sep	440.3428571	0.000214642	0.101024	0.627631557	44.4851968	276.373073
14	Daucus carota	Jun	Aug	1646.592117	0.00120052	0.565039789	0.39617149	930.3900625	652.3328531
15	Echium vulgare	May	Aug	16305.25	0.002099912	1.108514536	0.631346029	18074.60664	10294.25484
16	Erica tetralix	Jun	Sep	3605.47	NA	0.0703	NA	253.464541	0

The data on plant communities was compiled in a spreadsheet table (*Table 8*). This file contains one sheet per month, with only the species flowering in this specific month included. The percentage of presence and cover percentage of each species was compiled in this Excel file to perform the nectar and pollen production calculation for each month of each plant community. The full data can be found in Supplementary data 2: PC_nectar_production.

Table 8: Table compiling the data obtained from SynBioSys. Each plant community has two columns, the first one -a- depicts the percentage cover of a species and the second -b- is the percentage of faithfulness.

Plant community	42		43	
	a	b	a	b
Salix cinerea	0	0	5	4
Salix alba	0	0	3	14
Salix viminalis	0	0	0	0
Bellis perennis	0	0	0	0
Ficaria verna s.l.	0	0	39	17
Salix repens	0	0	0	0
Salix triandra	0	0	0	0
Prunus spinosa	0	0	13	5
Salix aurita	1	2	0	0
Salix fragilis	0	0	0	0
Salix aurita x cinerea	0	0	0	0
Salix daphnoides	0	0	0	0
Salix dasyclados	0	0	0	0
Salix caprea	1	2	5	3
Salix purpurea	0	0	0	0
Salix spec.	0	0	0	0
Salix aurita/cinerea	0	0	0	0
Salix pentandra	0	0	0	0
Ranunculus spec.	0	0	0	0

The nectar and pollen production data from FloRes were appended as the last two columns of the table (*Figure 27)*. Following the mathematical equation presented in *Section 2.2.2 (Equation (2))*, the total production of nectar and pollen of the plant community was calculated. For each plant community, the total below its first column -a-, depicts the nectar production and the second -b- the pollen.

TRANSPOSE	=SUM(BZ4:BZ22*CA4:CA22*$CB$4:$CB$22)/10000*10000/1000						
	Column1	Column78	Column79	Column80	Column81	Column82	Column83
2	Plant community	42		43		nectar_sugar_m²	pollen_m²
3		a	b	a	b		
4	Salix cinerea	0	0	5	4	4414.836607	10503.24852
5	Salix alba	0	0	3	14	3064.784183	11819.99905
6	Salix viminalis	0	0	0	0	3064.784183	11819.99905
7	Bellis perennis	0	0	0	0	17.6647893	50.64789453
8	Ficaria verna s.l.	0	0	39	17	1.274724	183.483
9	Salix repens	0	0	0	0	3064.784183	11819.99905
10	Salix triandra	0	0	0	0	3064.784183	11819.99905
11	Prunus spinosa	0	0	13	5	176.9326864	22.13070825
12	Salix aurita	1	2	0	0	3064.784183	11819.99905
13	Salix fragilis	0	0	0	0	3064.784183	11819.99905
14	Salix aurita x cinerea	0	0	0	0	3064.784183	11819.99905
15	Salix daphnoides	0	0	0	0	3064.784183	11819.99905
16	Salix dasyclados	0	0	0	0	3064.784183	11819.99905
17	Salix caprea	1	2	5	3	3064.784183	11819.99905
18	Salix purpurea	0	0	0	0	3064.784183	11819.99905
19	Salix spec.	0	0	0	0	3064.784183	11819.99905
20	Salix aurita/cinerea	0	0	0	0	3064.784183	11819.99905
21	Salix pentandra	0	0	0	0	3064.784183	11819.99905
22	Ranunculus spec.	0	0	0	0	1.274724	183.483
23	Total	12.25913673	47.27999619	10000/1000	1006.892641		

Figure 27: Table of the combination of FloRes and SynBioSys data. The figure highlights the Excel calculation performed for obtaining the nectar sugar production of a plant community for a specific month following Equation (2). For each plant community, two columns are attributed: (a) The percentage of cover of the species, (b) the percentage of faithfulness. The first division by 10 000 corresponds to turning the values into percentages, while the multiplication by 10 000 represents the unit change from m² to ha and the last division represents the turning from mg to g of nectar sugar production.

This data on all worksheets (per month) was then compiled into a single double-entry table in the spreadsheet 'Combined final' to add in ArcGIS and join to the spatial data (*Table 9*). To perform the join, an extra attribute was added to the spatial data: the 'PC' label. The name was manually added to fit the right plant community and right resource (e.g. '6 – pollen').

Table 9: Final nectar and pollen production table per plant community per month.

PC	January	February	March	April	May	June	July	August	September	October	November	December
4 - nectar	0	0	9.196902	9.196902	9.196902	0	0	0	0	0	0	0
4 - pollen	0	0	35.82696	35.82696	35.82696	0	0	0	0	0	0	0
6 - nectar	0	0	81.65896	81.65896	81.65896	0	4.751403	4.751403	4.751403252	0	0	0
6 - pollen	0	0	276.3299	276.3299	276.3299	0	1.238889	1.238889	1.238889032	0	0	0
7 - nectar	0	0	40.06017	45.26136	46.19059	18.42692	86.40407	86.40407	86.40406875	2.3058923	0	0
7 - pollen	0	0	185.0356	194.4625	195.159	10.13277	33.37345	33.37345	33.3734463	3.5005978	0	0

The statement used in Raster Calculator to turn NoData values into 0 is the following:

$$Con(IsNull('raster\_name'),0,'raster\_name')$$

This statement checks whether a cell is Null in the raster. If it is, replaces it by 0, if it is not, replaces it by the raster value. This allows to easily sum up the rasters of different plant communities all together.

Appendix 2.3: Detailed methodology of method 3.

The detailed workflow utilised for method 3 can be seen in *Figure 28*.

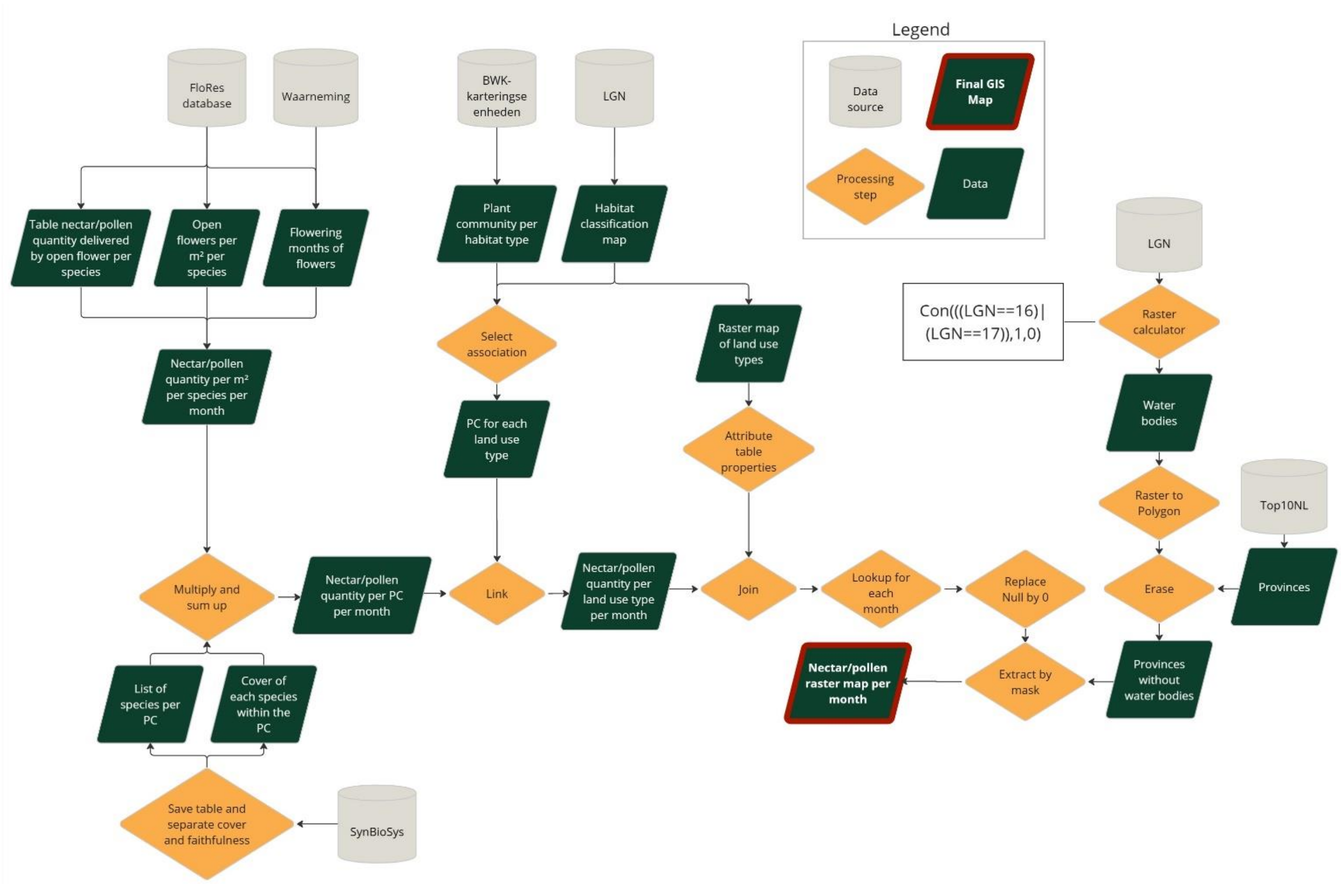

Figure 28: Detailed workflow diagram of method 3.

The associations made between LGN classes and BWK land uses were made to the best of my knowledge and examples can be found in *Table 10*. The rest of the associations are listed in Supplementary data 3: LGN_to_PC.

Table 10: Table listing the associations made between LGN and BWK classes.

LGN ID	LGN class dutch	BWK	Plant community	Plant community selected	Reason
1	Agrarisch gras	Soortenarm permanent cultuurgr	r12RG09, r12RG01, r16RG23	r12RG09, r12RG01, r16RG23	
2	Maïs	Akker	r31	r31	
3	Aardappelen	Akker	r31	r31	
4	Bieten	Akker	r31	r31	
5	Granen	Akker	r31	r31	
6	Overige landbouwgewassen	Akker	r31	r31	
8	Glastuinbouw	Kwekerij of serre	NA	NA	
9	Boomgaarden	Laagstamboomgaard	NA	NA	
10	Bloembollen	Akker	r31	r31	
11	Loofbos	Eiken- en beukenbossen' section	r45, r46	r45, r46	
12	Naaldbos	Naaldhoutbestand zonder/met o	r44	r44	
16	Zoet water		NA	NA	
17	Zout water	Brak of zilt water	r01Aa01, r02, r04Bb01, r04Ca01, r05Aa01, r05Aa02	r04Bb01	Only this one has one of top50 plants

From there, similar work as for Method 2 was made (see *Section 2.2.2* and *Appendix 2.2*). *Table 11* depicts the table that resulted from this work, organised slightly differently for fitting to the raster data. For each value (i.e. land use class of LGN) was attributed 24 columns with the 12 first being the nectar values per month and the following the pollen values. The full data can be found in Supplementary data 3: Production_per_PC.

Table 11: Table listing the final double-entry table used for joining data to the raster data.

Value	January - n	February -	March - ne	April - nect	May - necta	June - nect	July - necta	August - ne	Septembe	October - r	November	December	January - p	February -	March - po	April - polle	May - polle
1	0.08538	0.08538	0.08546	2.50976	6.34164	10.146	14.5487	14.5479	12.0399	2.57875	0.08538	0.08538	0.2448	0.2448	0.25703	4.14434	6.63576
2	0	0	0	1.02523	1.43097	9.77727	12.4093	12.3937	9.63441	6.04563	0.45959	0	0	0	0	1.30096	1.54262
3	0	0	0	1.02523	1.43097	9.77727	12.4093	12.3937	9.63441	6.04563	0.45959	0	0	0	0	1.30096	1.54262
4	0	0	0	1.02523	1.43097	9.77727	12.4093	12.3937	9.63441	6.04563	0.45959	0	0	0	0	1.30096	1.54262
5	0	0	0	1.02523	1.43097	9.77727	12.4093	12.3937	9.63441	6.04563	0.45959	0	0	0	0	1.30096	1.54262
6	0	0	0	1.02523	1.43097	9.77727	12.4093	12.3937	9.63441	6.04563	0.45959	0	0	0	0	1.30096	1.54262
8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
10	0	0	0	1.02523	1.43097	9.77727	12.4093	12.3937	9.63441	6.04563	0.45959	0	0	0	0	1.30096	1.54262

The data compiled in this table turns into the value of the raster when using Lookup, which was made for each month for nectar and pollen. The same conditional statement as the one in method 2 (see *Appendix 2.2*) was made in raster calculator to replace NoData values by zeros.

Appendix 2.4: Detailed methodology of method 4.

The detailed workflow used for method 4 can be found in *Figure 29* and *Figure 30*.

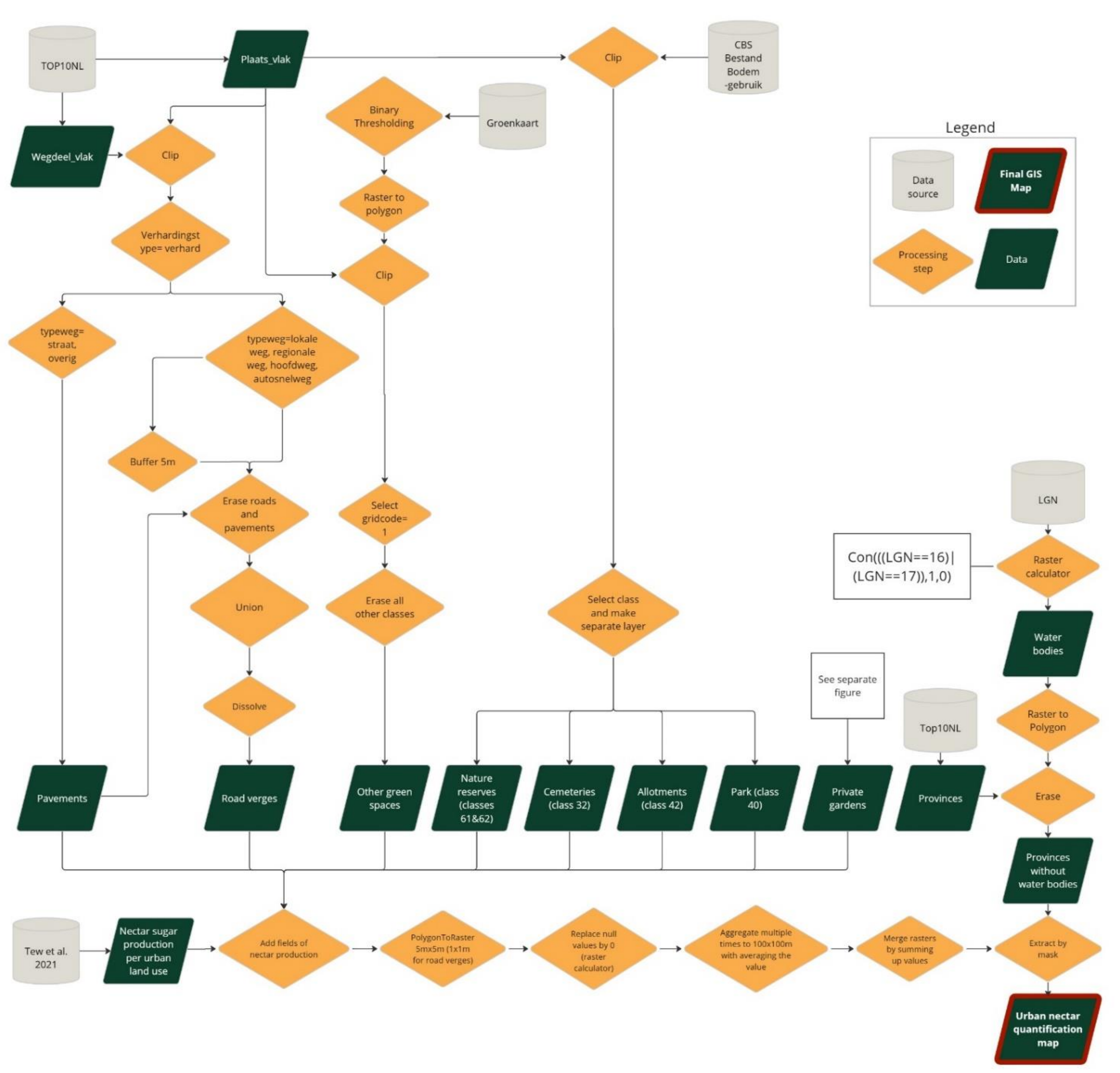

Figure 29: Detailed workflow diagram of method 4.

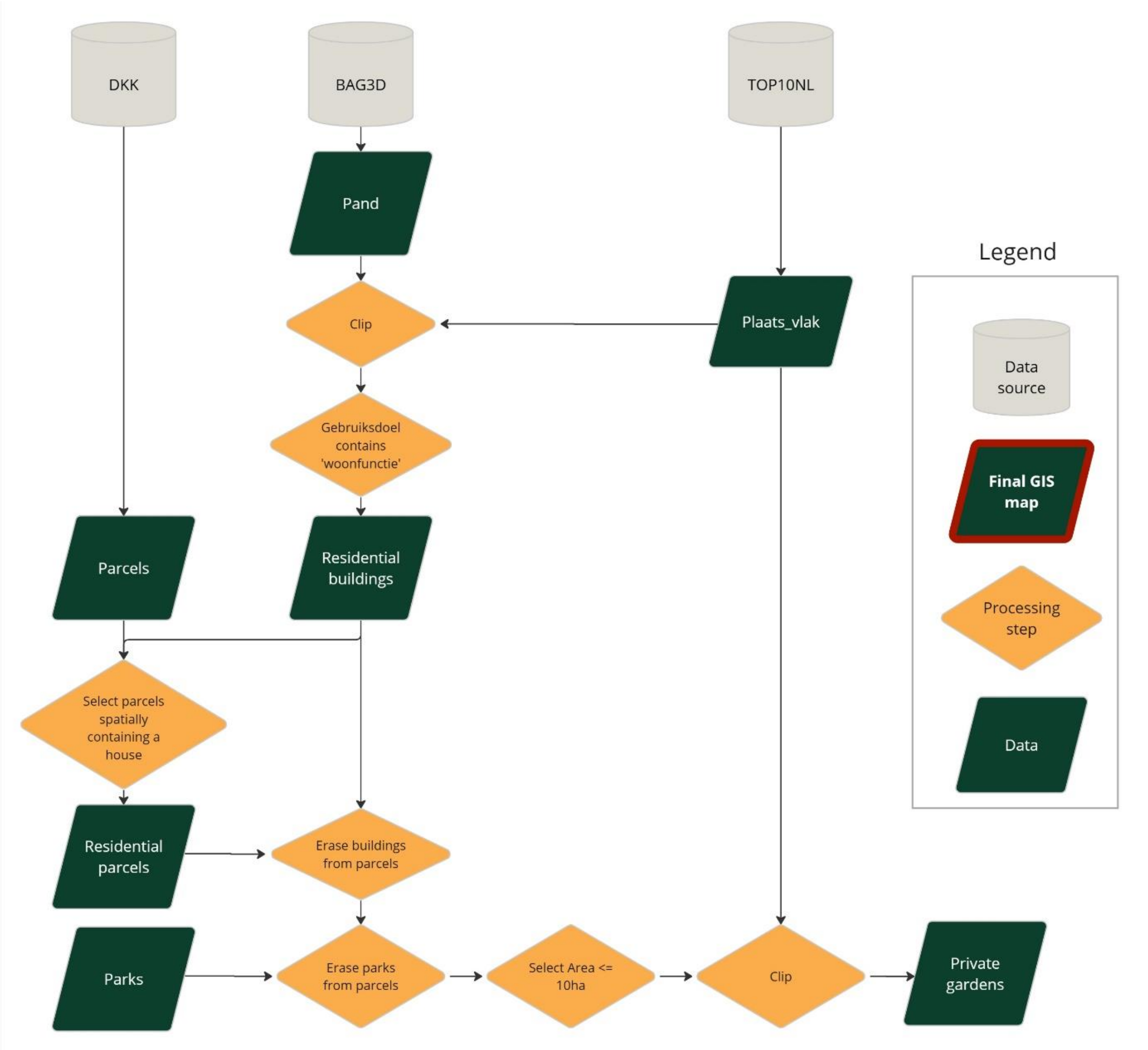

Figure 30: Detailed workflow diagram of the private gardens in method 4.

Four of the eight land use classes were directly derived from the data sources, while four other required further processing. Following is more detailed information on these four.

Pavements have been derived from the TOP10NL Wegdeel_vlak layer. This layer delivers all the pathways with multiple attributes, including the type of pavement ('verhardingstype') which has been used to select only the paved ways. These account for all the roads and streets, and it was chosen to select as pavement only those classified as streets and the 'others' which is how most bike lanes are classified (i.e. 'straat', 'overig') for the attribute 'typeweg'. Looking at known examples revealed that it also included some concrete-paved streets. Some of these streets are taken out when clipping the roads to the urban areas, but some remain and it should be kept in mind that this layer is not fully accurate.

Road verges were obtained through creating a buffer around the main roads, which were defined as those classified by 'lokale weg', 'regionale weg' and 'hoofdweg' in the 'typeweg' attribute. The buffer was made 5m large, and the footprint of the pavements and roads has then been deleted from the feature (using the geoprocessing tool 'Erase'). To avoid double counting, the intersections of these buffer have been removed through using the Union tool. Throughout this process, some incorrect geometry was identified and fixed through the combination of Check Geometry and Repair Geometry. The repair geometry has been performed multiple times in a row to reduce the amount of incorrect geometries. After 3 times, two elements were still incorrect (self-intersection) and were therefore deleted from the data.

Private gardens were obtained from a combination of the cadastral map DKK (ESRI Nederlands, 2023) and the buildings layer BAG3D (ESRI Nederlands, 2020). The BAG3D contains an attribute of type of use (gebruiksdoel) for the buildings. As a first step, residential buildings were extracted from selecting only the buildings containing the residential function (woonfunctie) in this attribute. The parcels were then spatially linked (Spatial Join) to the residential buildings so that the parcel number is included in the attributes of a building if the center of gravity of this building is in the parcel. This new list of attributes was then linked back (Join Features) to the parcels based on the parcels ID. The residential parcels were then identified as those who had the extra information from the buildings. The spatial join was used in this order and not the opposite because the function 'have their center in' applies to the layer being added data to. This means otherwise it would be joining data based on whether the center of the parcel was inside a building. Furthermore, the lack of precision of the layers do not allow to use the 'intersect' function to make the spatial join.

The private gardens finally were obtained by substracting the building footprint from each residential parcel using the function 'erase'. Checking some examples, I also realised some parks were included and therefore also used 'erase' with the parks layer to increase the accuracy. Another clip was required at the end because of large gardens for which the house was in the urban area, but a part of the garden was going outside.

Other green spaces were obtained from the Groenkaart (RIVM, 2020) combined to the use of the 'Erase' function with all previous classes. The differentiation between green and non-green has been performed through 'Binary Thresholding', and the raster has been converted to a polygon layer using the tool 'raster to polygon'.

Following the completion of these steps, these polygon shape files were then turned into rasters. This was made through using the 'PolygonToRaster' geoprocessing tool, and the Conditional IsNull statement in the raster calculator (to replace NULL by 0 in order to accurately merge the different rasters, see *Appendix 2.2*) by starting with 5m x 5m raster cell, and then aggregating to 10m x 10m, 20m x 20m and finally 100m x 100m raster cell using the mean value. This allows to not lose any information in the process and make a heatmap where a cell completely covered by one of the land uses has the full nectar sugar production calculated by Tew et al. (2021), while a cell covering only a part of it would have a proportional nectar sugar production value.

As the road verges are very linear objects, the calculation was started with 1m x 1m cells, and then 2m x 2m, 4m x 4m, 20m x 20m and 100m x 100m. The road verges raster layer displayed horizontal lines for which no reason was found. The road verges were then 'Dissolved' to aggregate them to a single object which allowed to reduce the number of lines (these lines did not appear on smaller areas). These lines are isolated cells and therefore it has been chosen to continue with this as their values would go down when aggregating. However a further study should look more into detail and try to find a fix.

Appendix 2.5: Detailed methodology of method 3+4 and the comparison with demand.

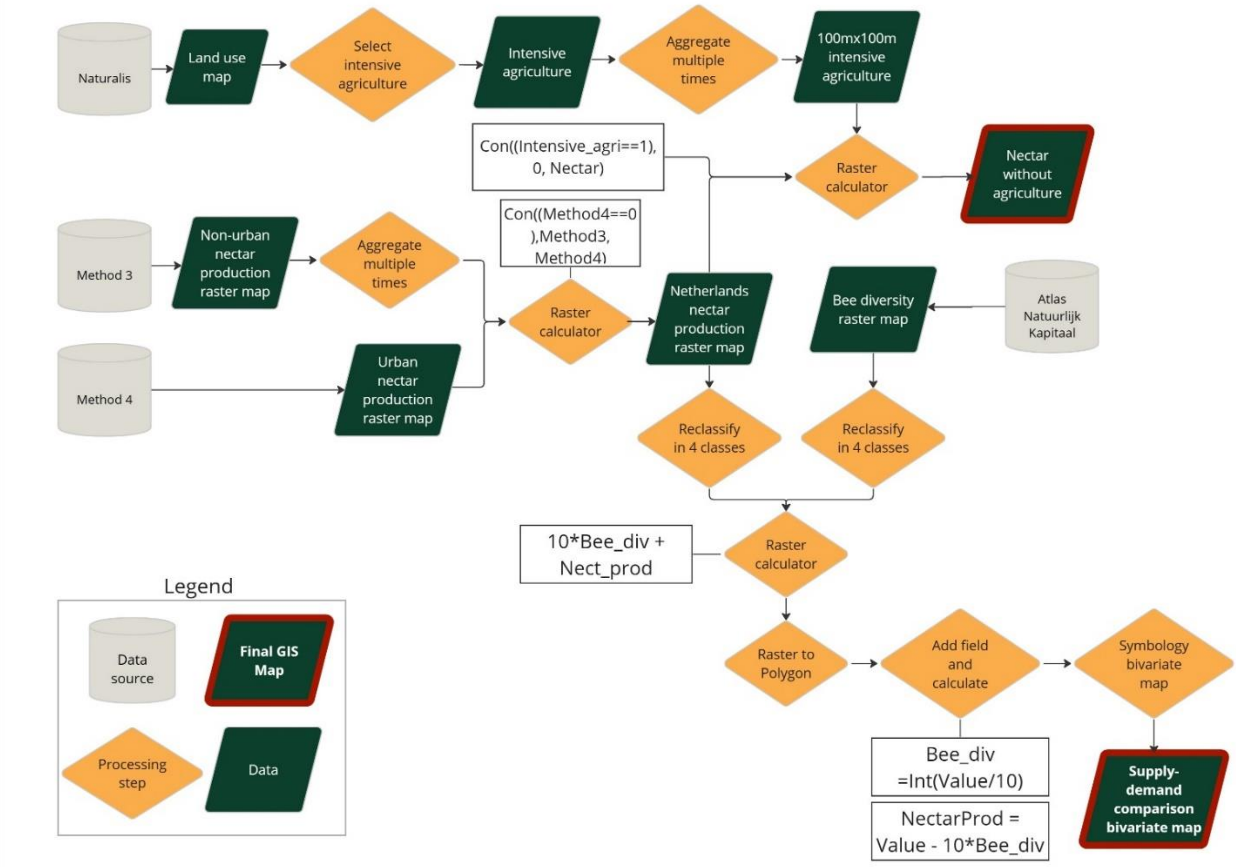

Figure 31: Detailed workflow diagram of methods 3+4 and the combination with the demand side.

Appendix 3: Experts consulted.

Table 12: List of the persons I had the opportunity to sit down with and discuss my study.

Koos Biesmeijer	Zina Broeksma	Arjen de Groot
Ana Feijoo Quezada	Leon Marshall	Merijn Moens
Kaixuan Pan	Marco Roos	Michiel Scham
Marten Schoonman	Maarten van’t Zelfde	

Appendix 4: Monthly maps of the different methods.

Appendix 4.1: Monthly maps of method 1.

The monthly maps produced by method 1 are depicted in *Figure 32, Figure 33* and *Figure 34*.

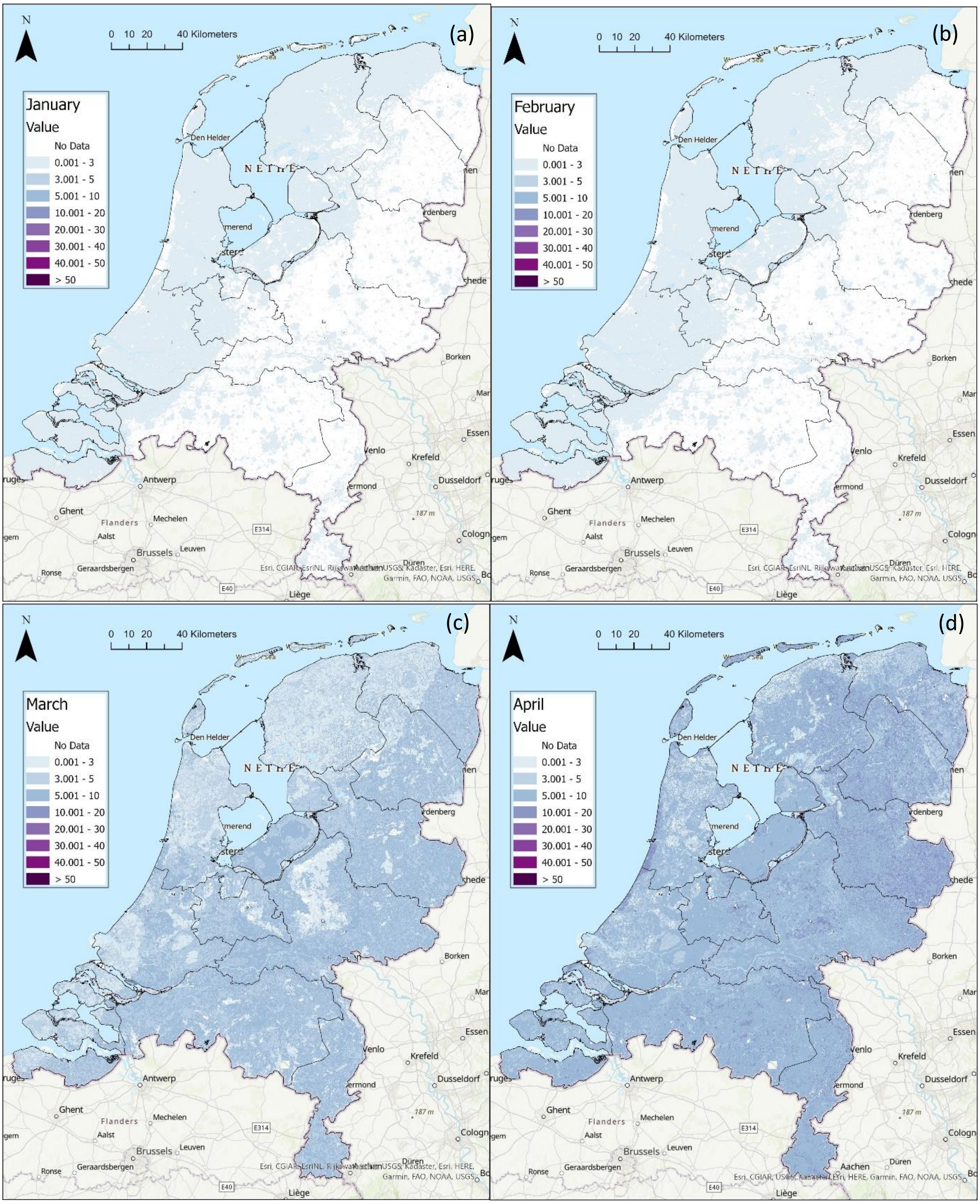

Figure 32: Distribution of the attractiveness index for pollinators in January (a) to April (d) of 2022.

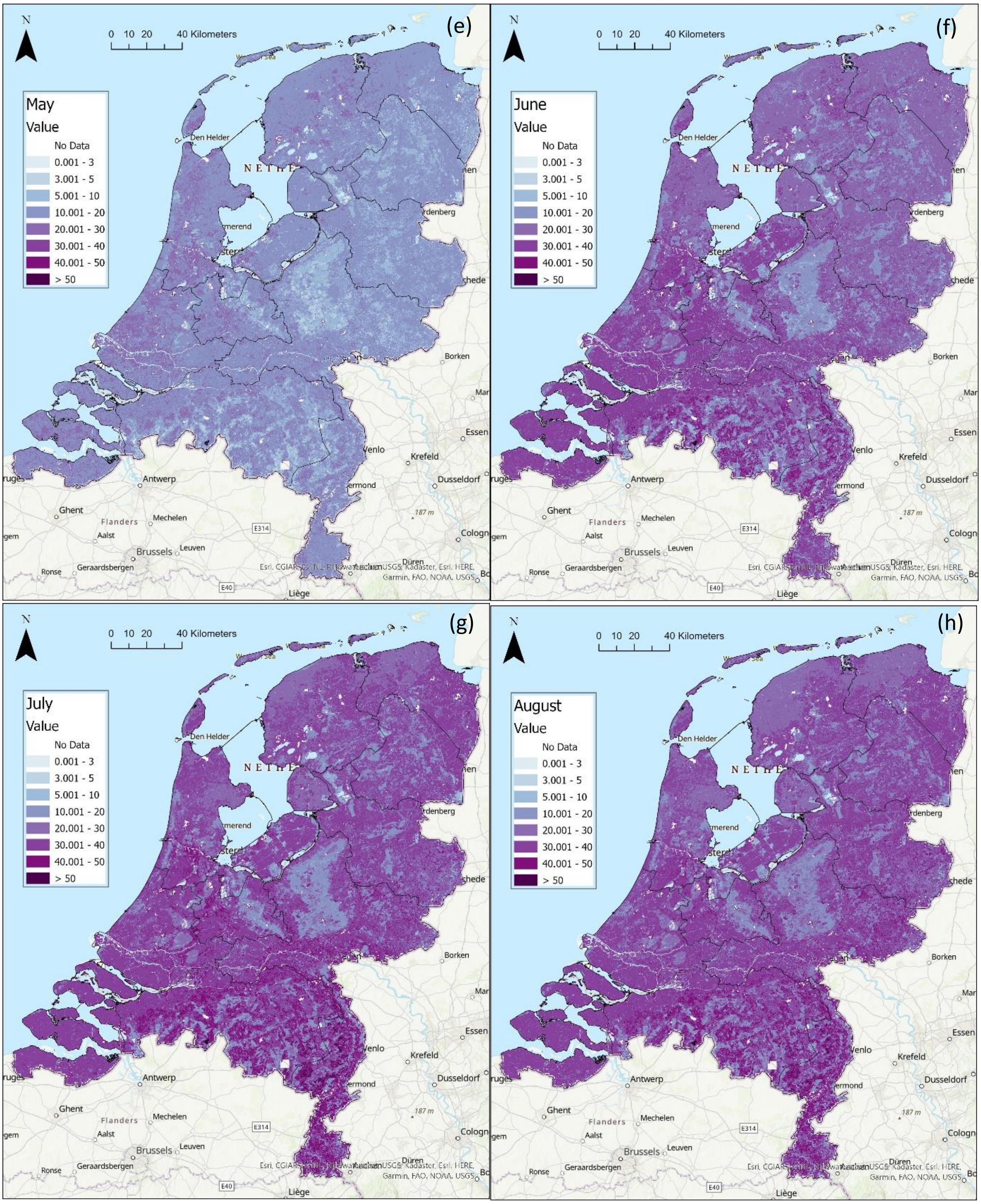

Figure 33: Distribution of the attractiveness index for pollinators in May (e) to August (h) of 2022.

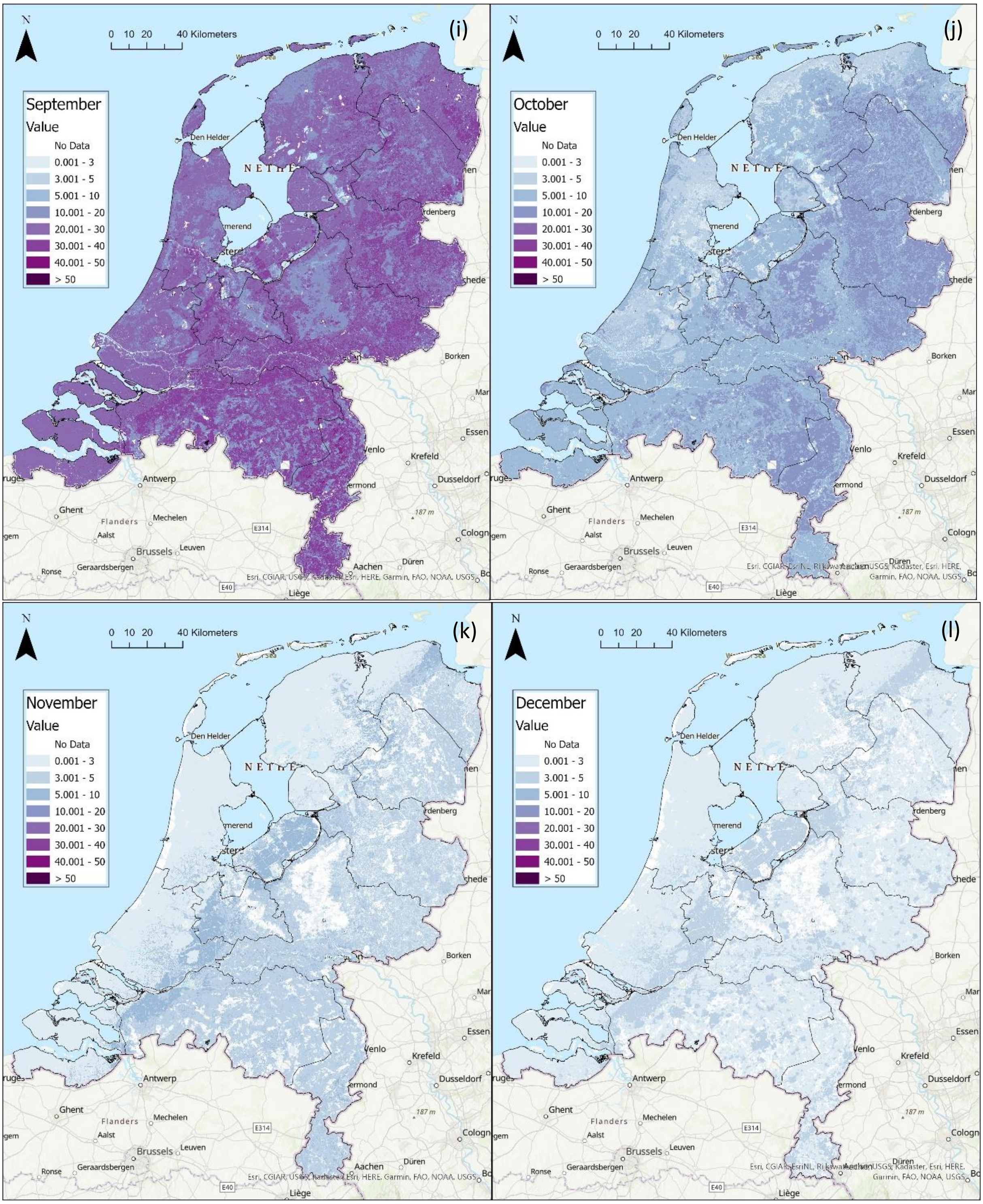

Figure 34: Distribution of the attractiveness index for pollinators in September (i) to December (l) for 2022.

Appendix 4.2: Monthly maps of method 2 for nectar.

The monthly nectar maps produced by method 2 are depicted in *Figure 35, Figure 36* and *Figure 37.*

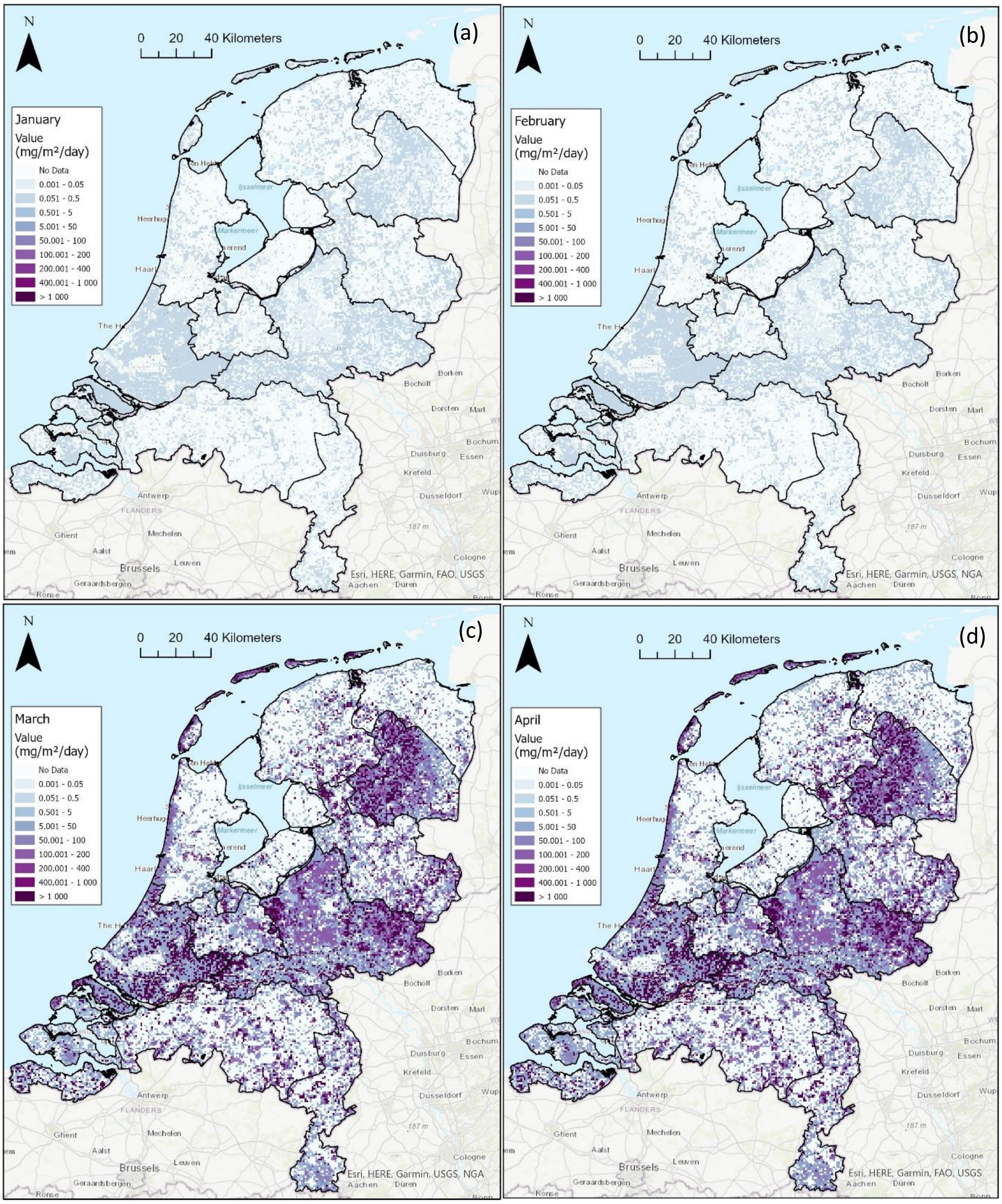

Figure 35: Distribution of the nectar production from method 2 in January (a) to April (d) for 2022.

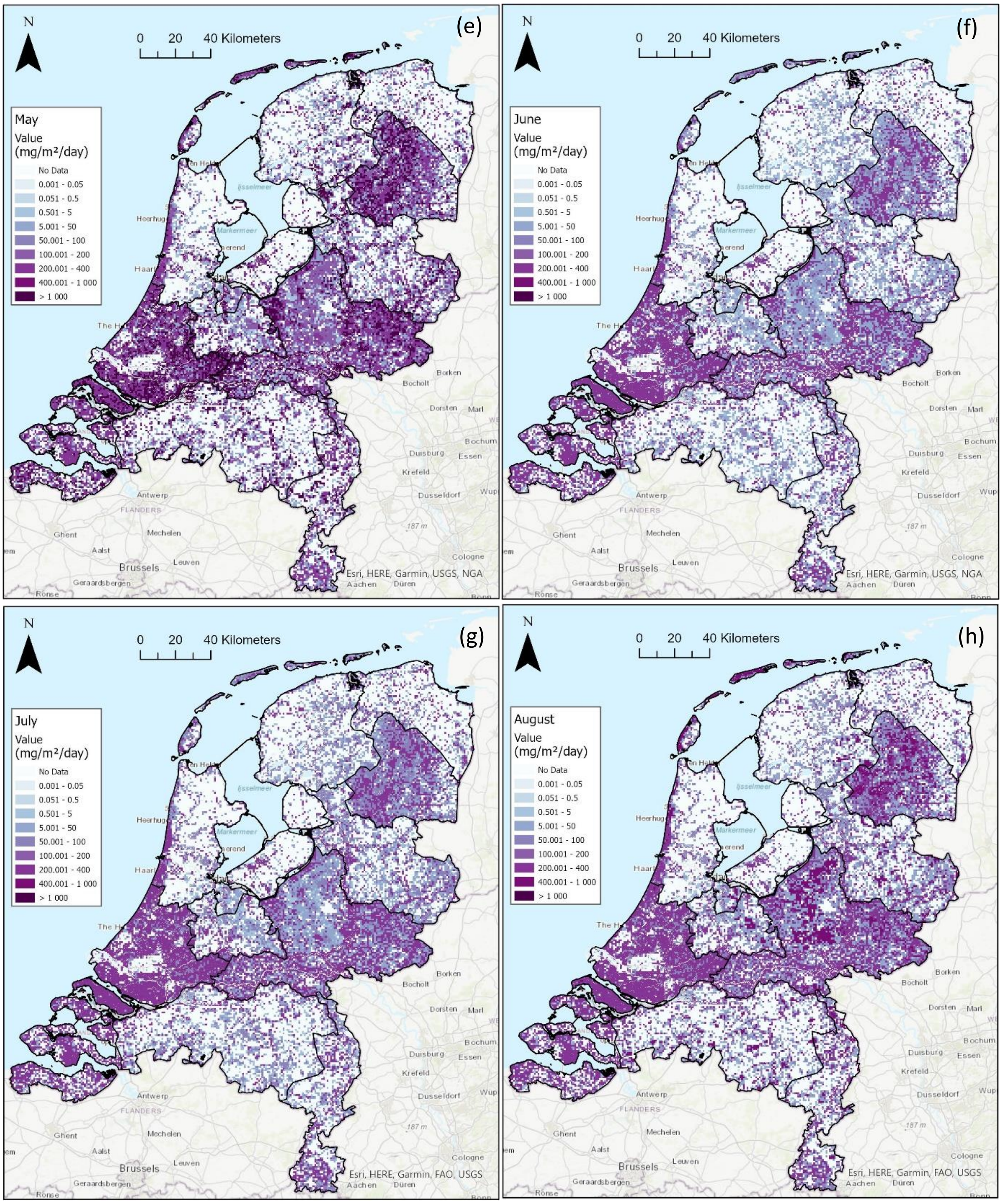

Figure 36: Distribution of the nectar production from method 2 in May (e) to August (h) for 2022.

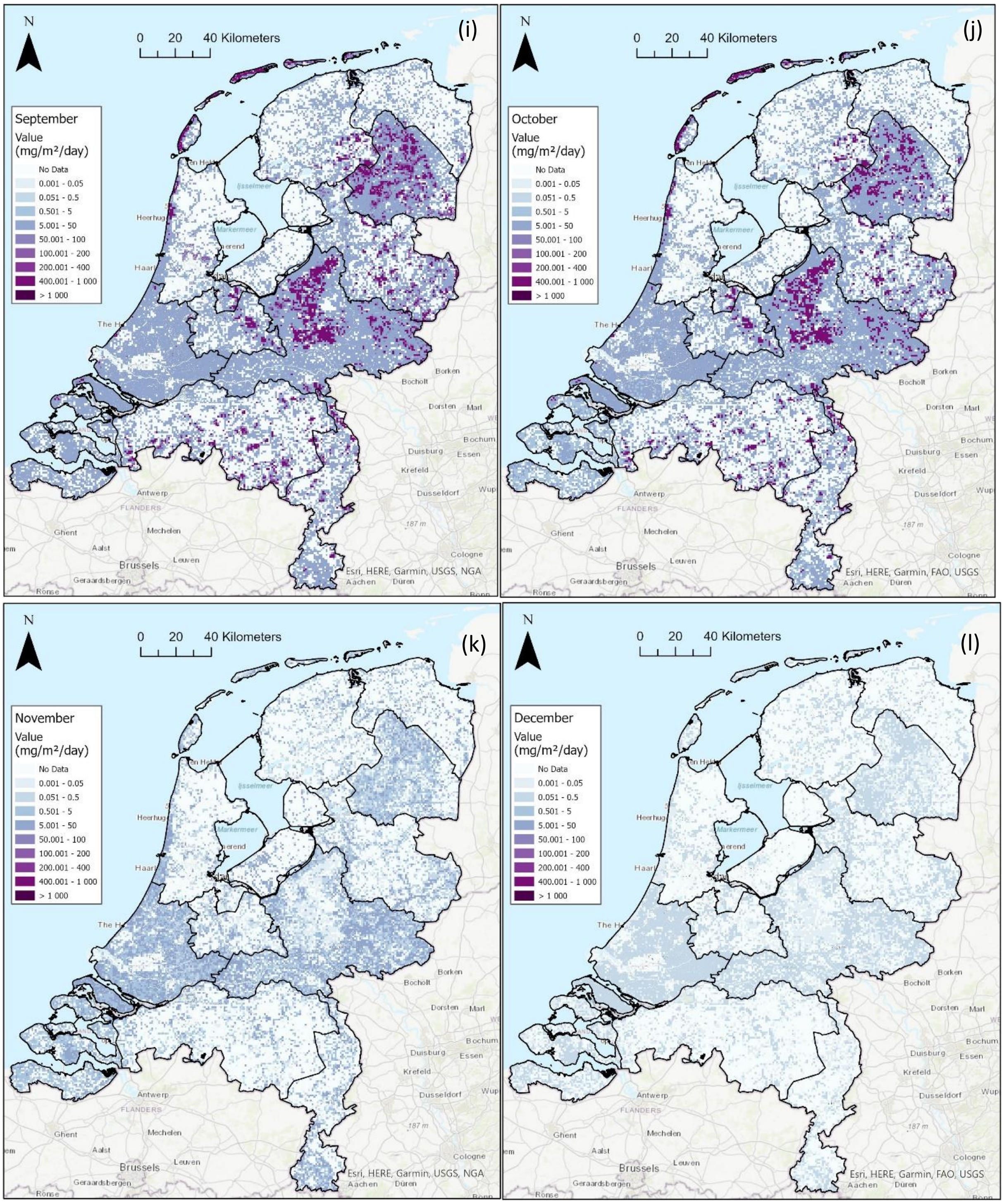

Figure 37: Distribution of the nectar production from method 2 in September (i) to December (l) for 2022.

Appendix 4.3: Monthly maps of method 2 for pollen.

The monthly pollen maps produced by method 2 are depicted in *Figure 38, Figure 39* and *Figure 40*.

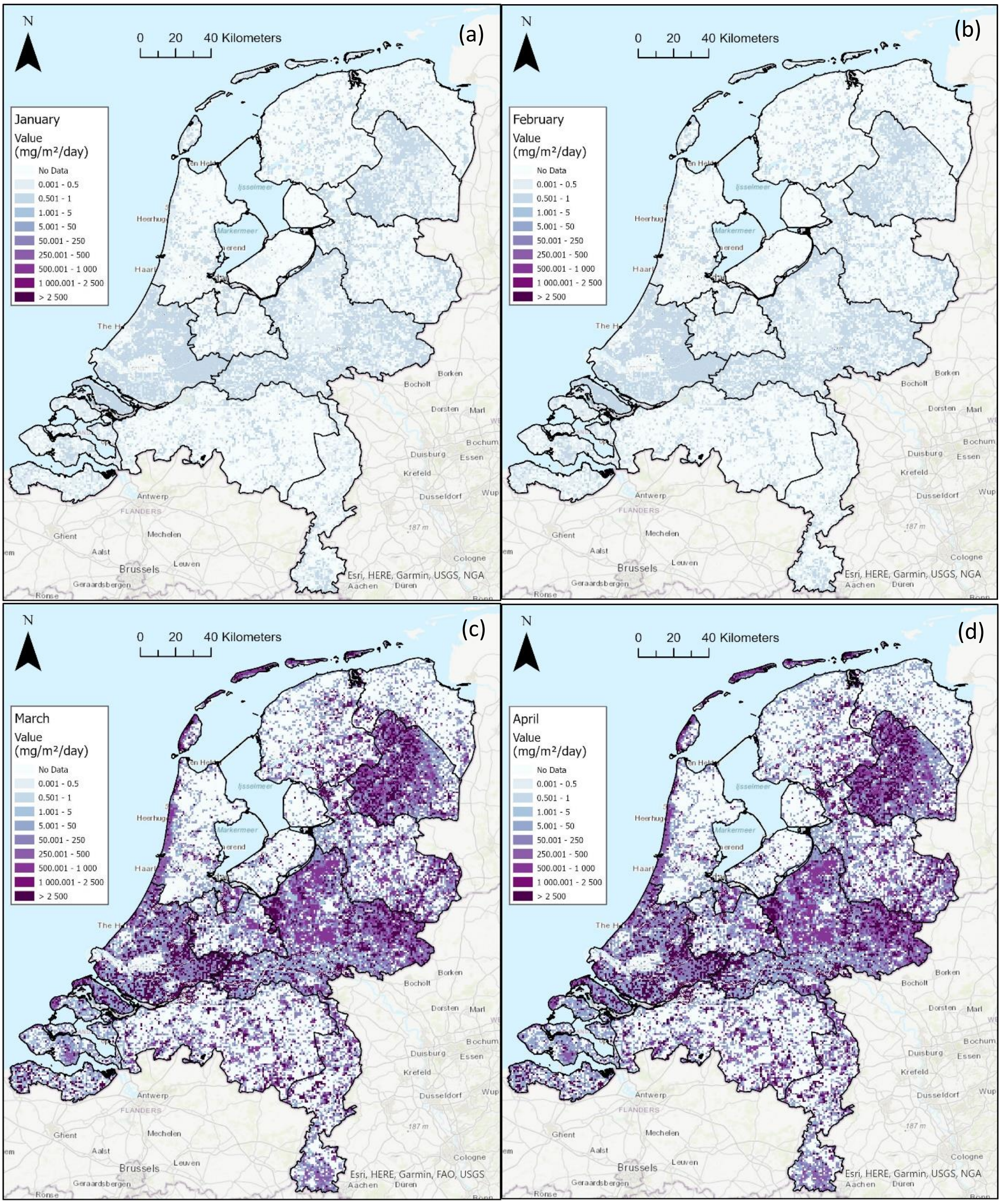

Figure 38: Distribution of the pollen production from method 2 in January (a) to April (d) for 2022.

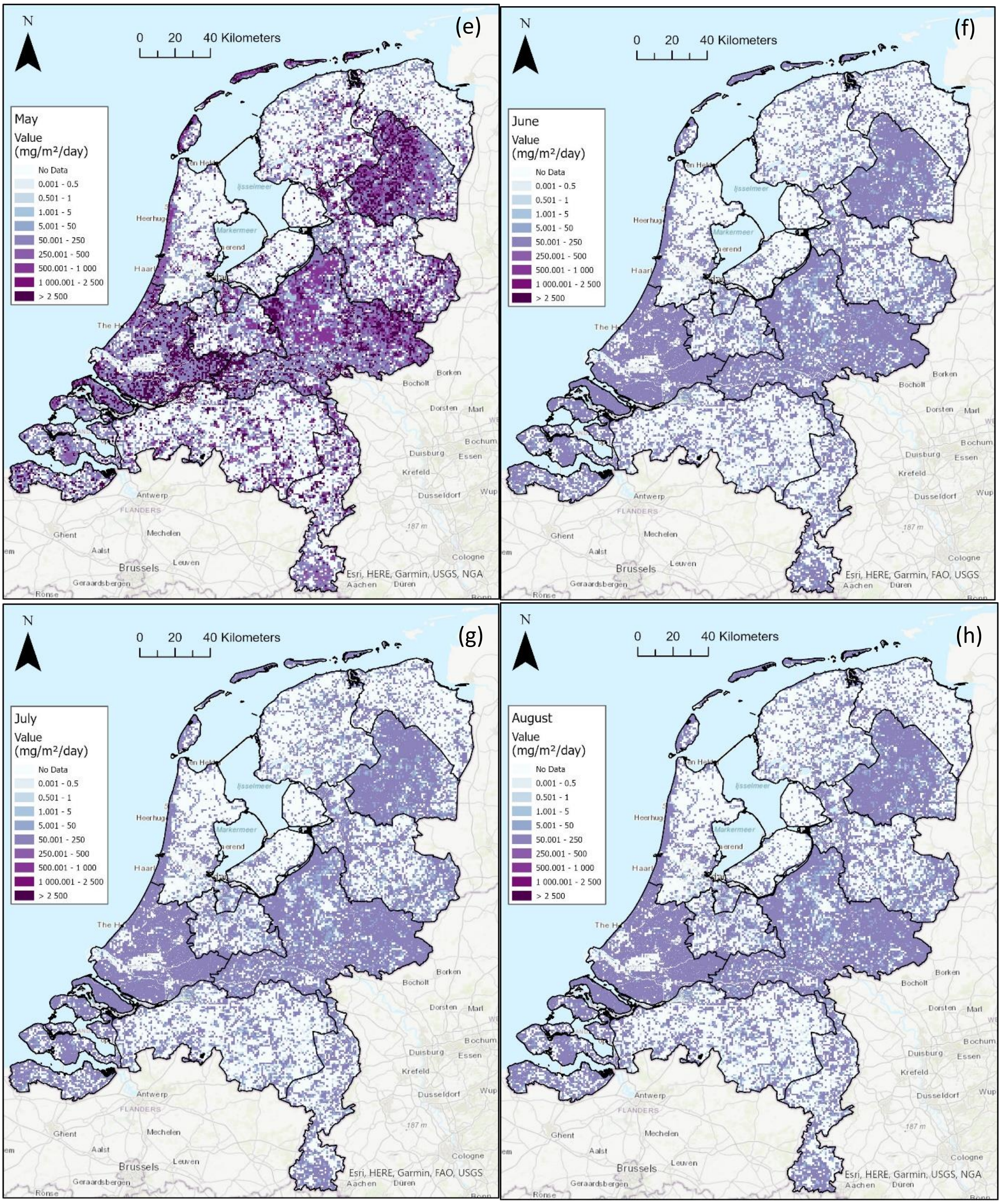

Figure 39: Distribution of the pollen production from method 2 in May (e) to August (h) for 2022.

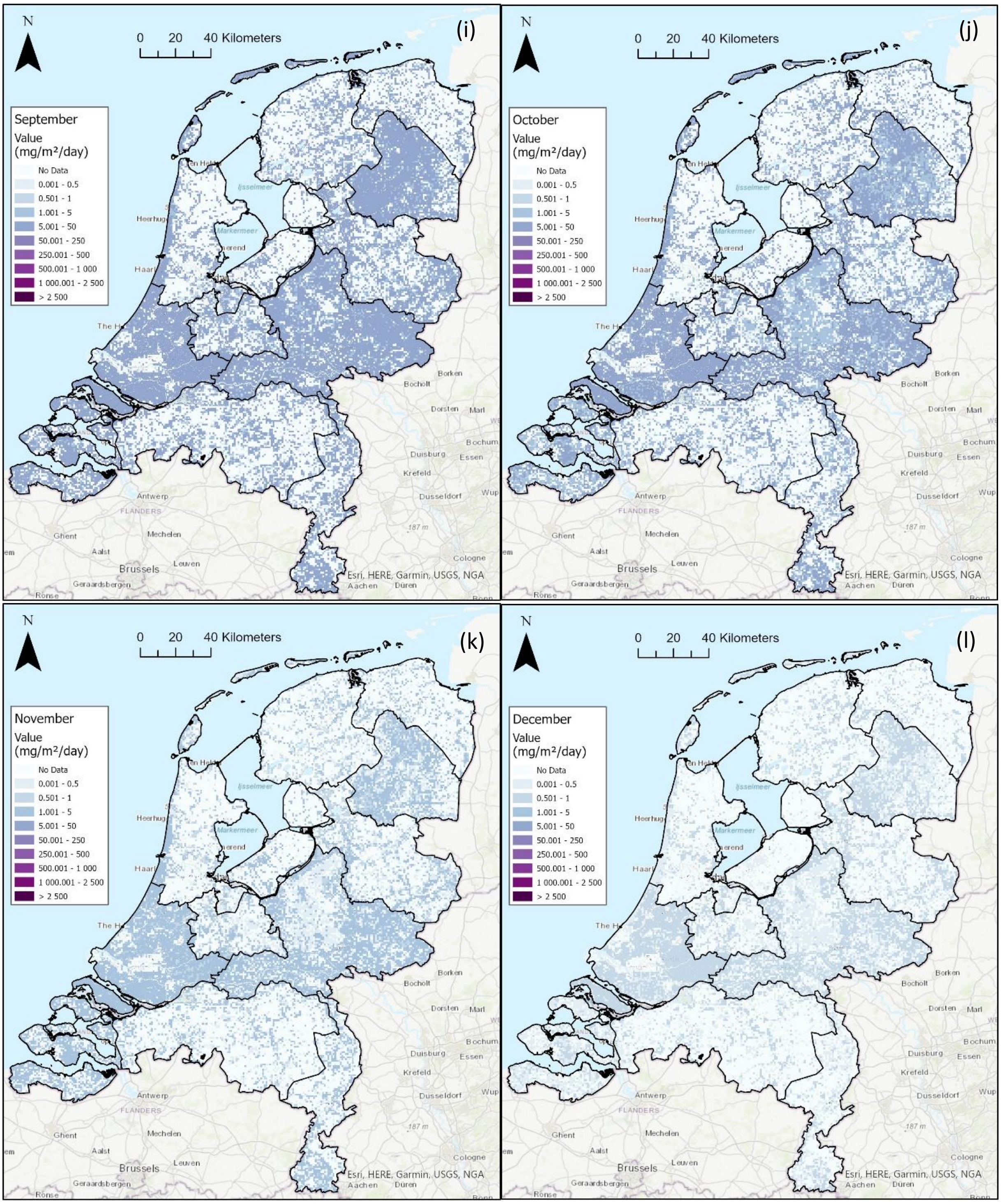

Figure 40: Distribution of the pollen production from method 2 in September (i) to December (l) for 2022.

Appendix 4.4: Monthly maps of method 3 for nectar.

The monthly nectar maps produced by method 3 are depicted in *Figure 41, Figure 42* and *Figure 43*.

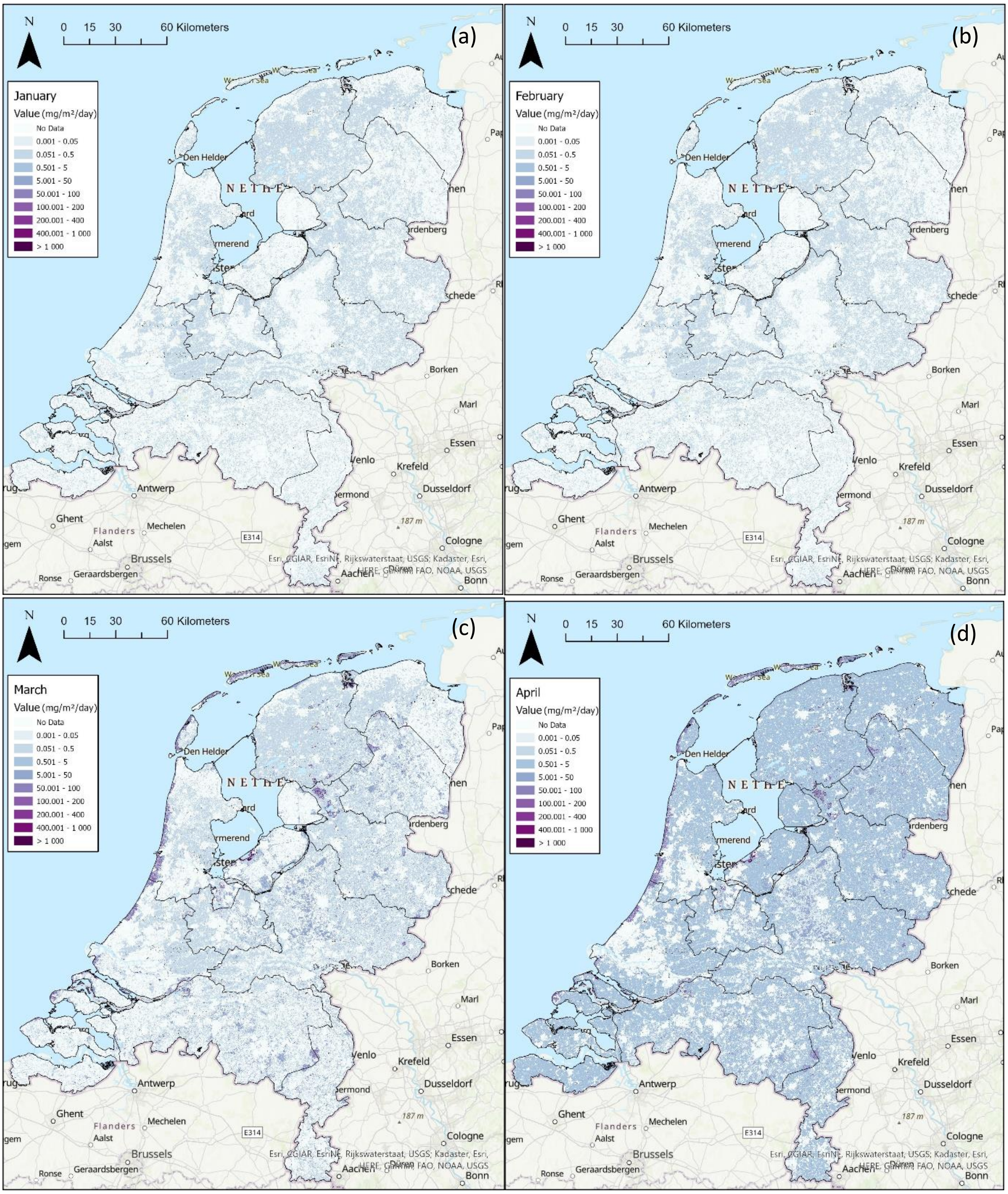

Figure 41: Distribution of the nectar production from method 3 in January (a) to April (d) for 2022.

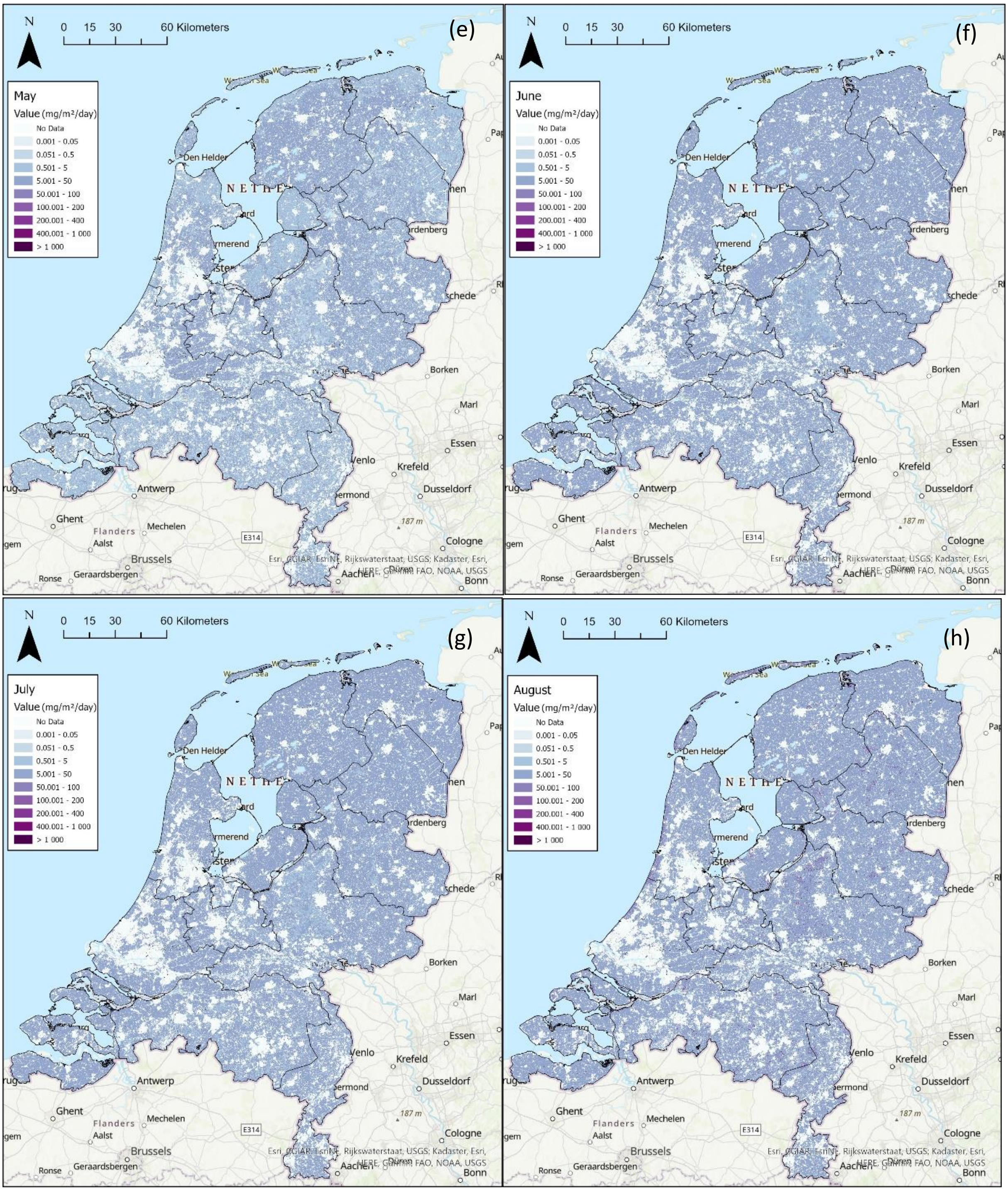

Figure 42: Distribution of the nectar production from method 3 in May (e) to August (h) for 2022.

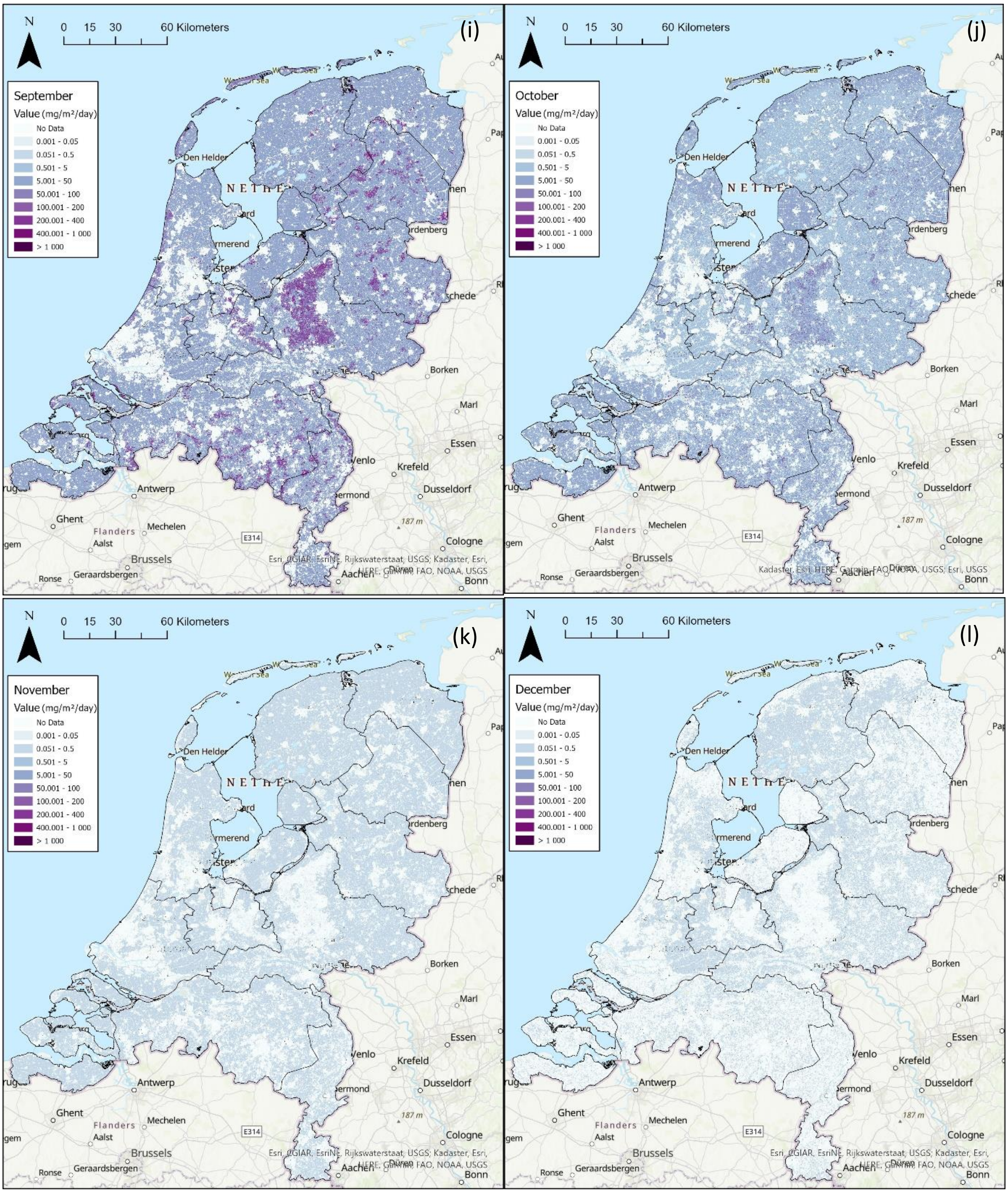

Figure 43: Distribution of the nectar production from method 3 in September (i) to December (l) for 2022.

Appendix 4.5: Monthly maps of method 3 for pollen.

The monthly pollen maps produced by method 3 are depicted in *Figure 44, Figure 45* and *Figure 46*.

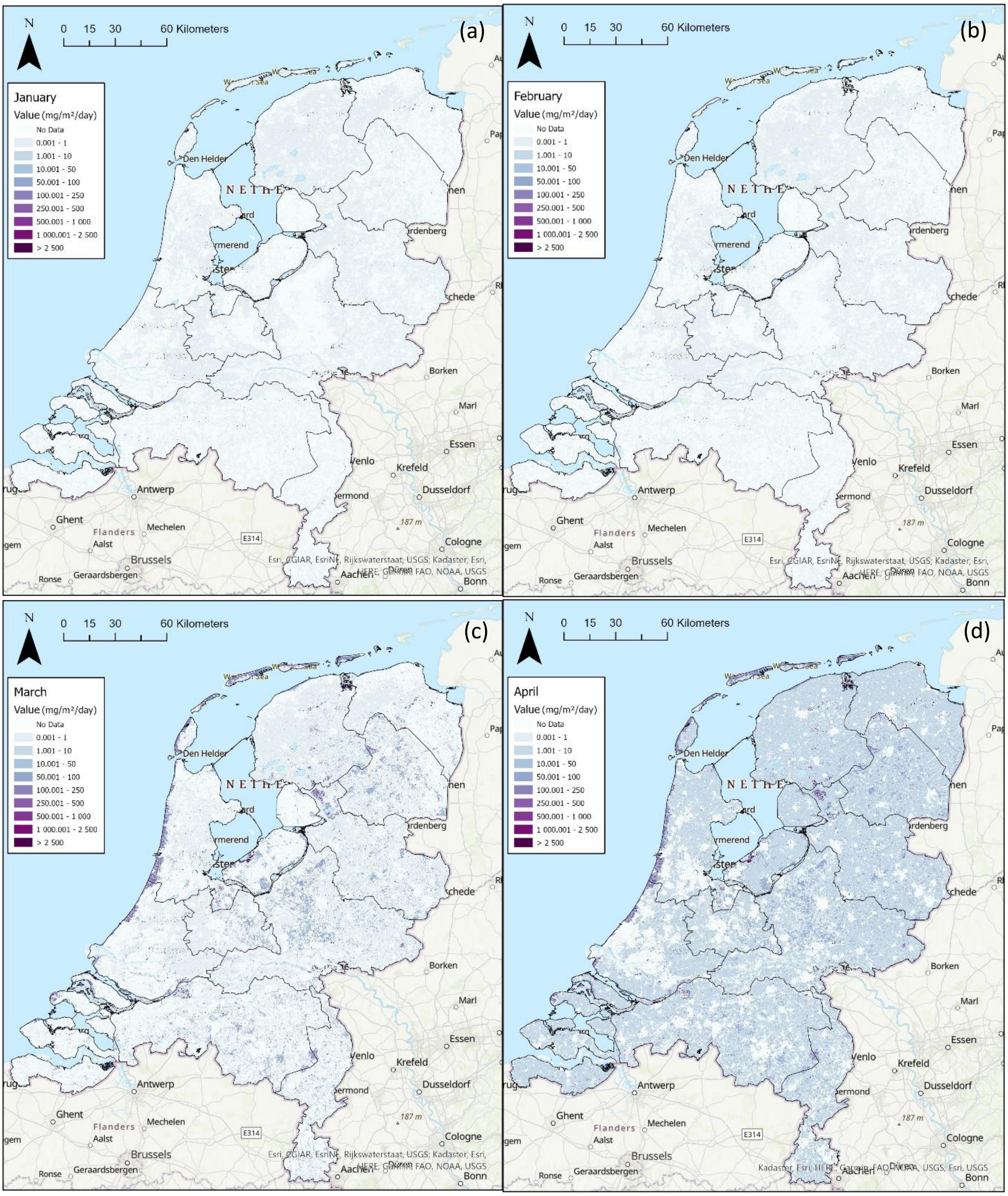

Figure 44: Distribution of the pollen production from method 3 in January (a) to April (d) for 2022.

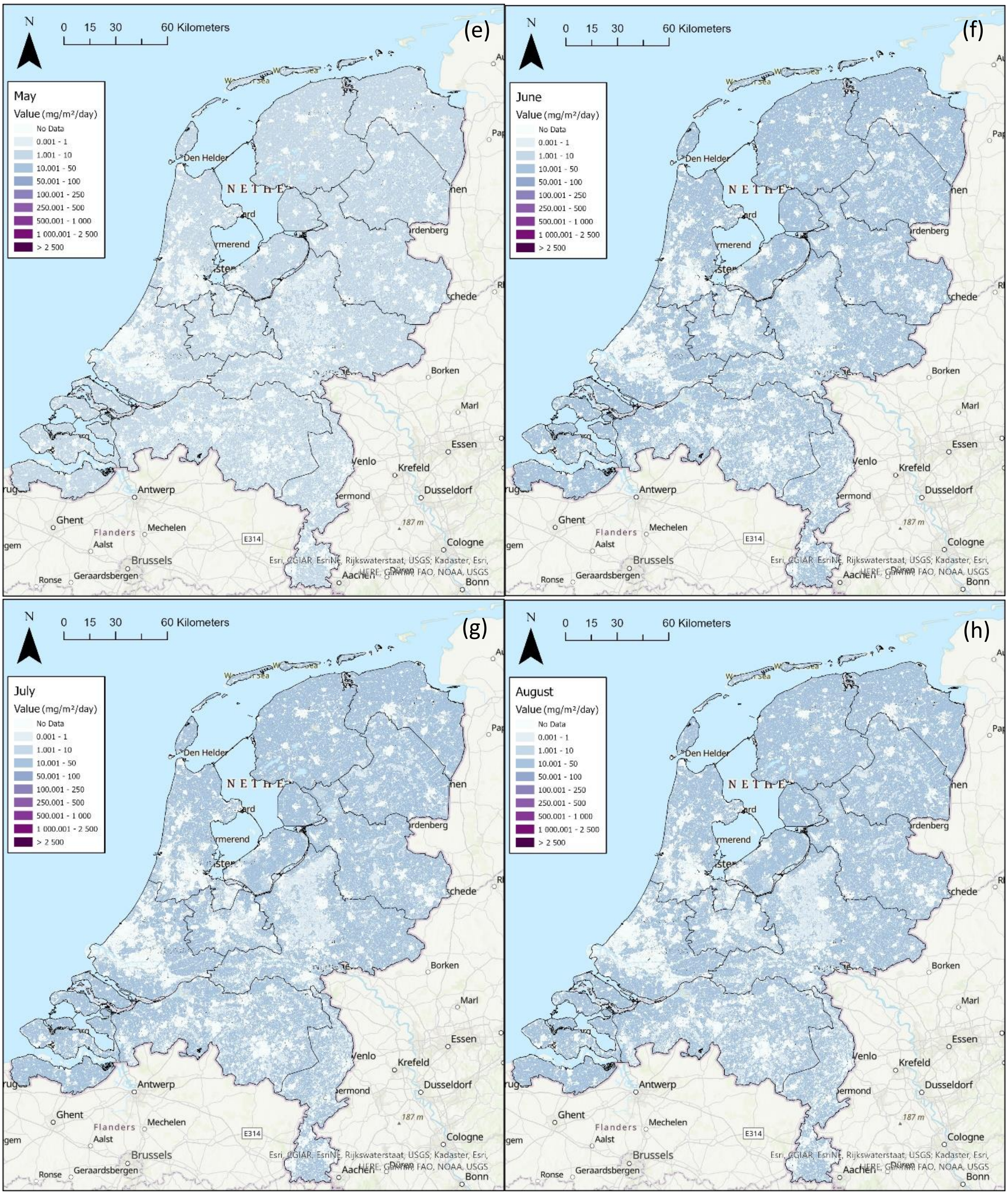

Figure 45: Distribution of the pollen production from method 3 in May (e) to August (h) for 2022.

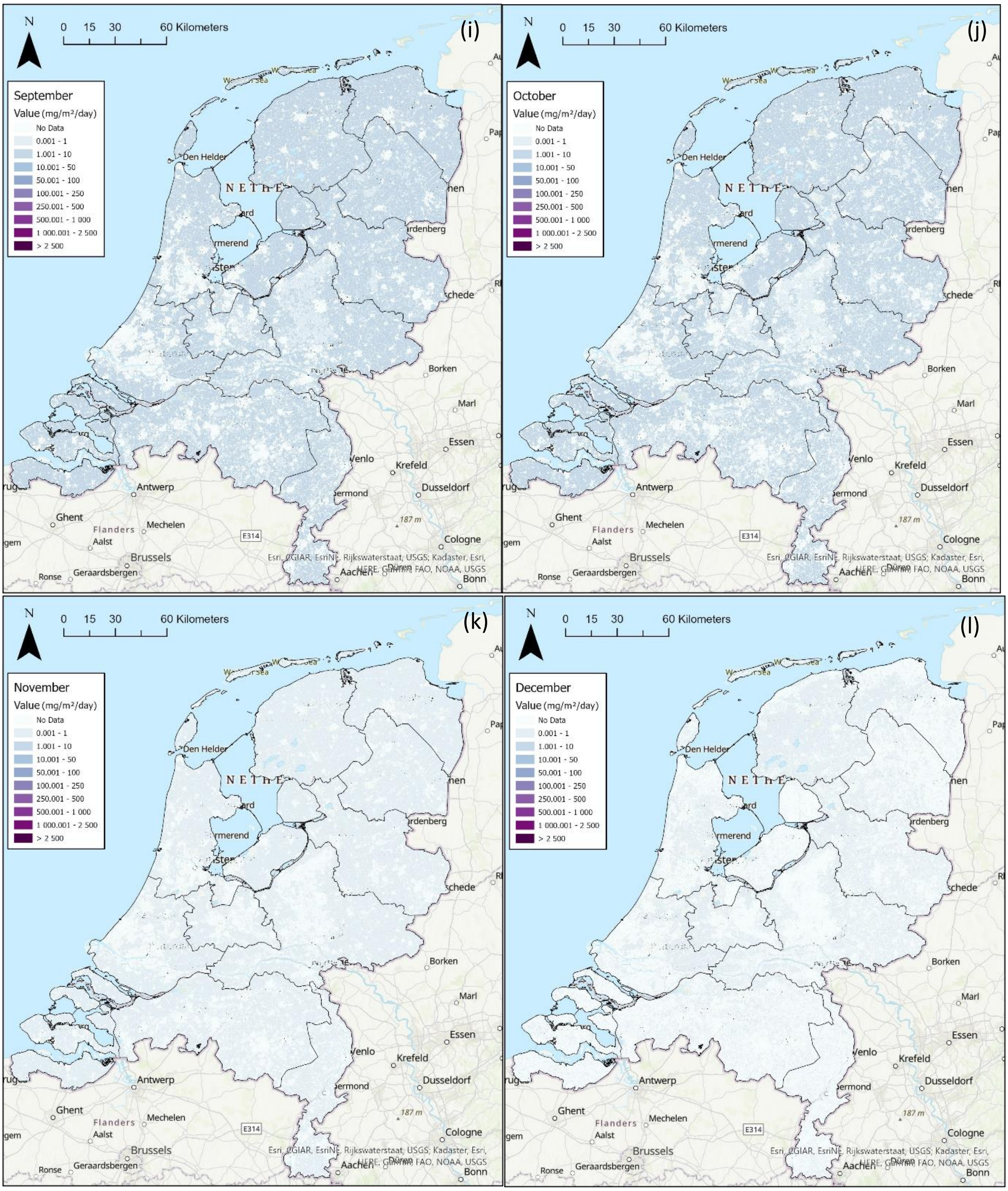

Figure 46: Distribution of the pollen production from method 3 in September (i) to December (l) for 2022.