Pollination service delivery for European crops: challenges and opportunities

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Short running title: Pollination delivery for Europe

Abstract

Crop pollination by bees has long been recognised as an ecosystem service of huge economic value; a large number of food crops depend upon pollination. Features across landscapes that are important for pollination delivery include: nesting habitats, floral resource availability at foraging distance, and climate. The conditions for presence/absence of pollinators are therefore complex and rely upon a combination of biotic and abiotic factors. To date there has been no easily available method for landowners to determine the potential of pollination delivery across the land effectively and rapidly. In this paper we develop a method that uses freely available datasets to remotely estimate the relative provision of pollination service delivery provided by bees across Europe at a 300m-pixel resolution. We then identify the potential pollination delivery and efficiency across Europe at country and regional level. This study illustrates an approach that obtains a first approximation for land managers to identify potential areas across landscapes to protect in order to enhance pollination service delivery.

Keywords: ecosystem services, pollination, landscape management, pollinator-dependent crops, species distribution modelling.

1. INTRODUCTION

Biodiversity loss and the degradation of ecosystems and the services they provide are major concerns facing modern society. In recent years, Ecosystem Services (ES) broadly defined as “the benefits of nature to households, communities, and economies” (Millennium Ecosystem Assessment, 2003; Boyd and Banzhaf, 2007; Fisher et al., 2009) have been progressively integrated in biodiversity policies such as the EU Biodiversity Strategy to 2020. Thus, as the importance of ES is recognized, is also appreciated that there is a need to find quick and accessible methods for landowners to be able to map and value the ecosystem service provision across their landscapes (Hauck et al., 2013; Maes et al., 2013).

The importance of insect pollination as an ecosystem service is widely recognised. An estimated 10% of the total economic value of European food production (€22 billion for Europe as a whole, and €14.2 billion for the European Union in 2005) is dependent upon insect pollination (Gallai et al., 2009). The first approach to model pollination at European scale was Maes et al. (2013). More recently, other European assessments have demonstrated that pollination by wild (e.g. bumblebees) and managed bees (e.g. honey bees) is required for 12 % of EU croplands and that it is essential for 3% (Schulp et al., 2014). Within this context a major concerns for farmers and land managers, therefore, is to conserve the delivery of pollination services to maintain crop production (Field, 2014). Specifically, bees and the nesting sites they inhabit are threatened by land-use changes, affecting in turn the service they provide (Kremen et al., 2007; Potts et al., 2010; Steffan-Dewenter et al., 2005; Vanbergen, 2013). There is indeed an explicit policy demand for better mapping ecosystem services in general and pollination services delivery in particular (Maes et al., 2013).

How to measure pollination service across landscapes is complex and research is currently being undertaken to better understand the ecology of pollinators, their relationship within landscape, and their contribution to crop yields. One approach for example has been to identify hotspots of global pollination benefit as well as countries with high vulnerability to a decline in pollination service (Lautenbach et al., 2012; Schulp et al., 2014). But, while the pollination benefit is important to quantify, what this approach does not characterize is the distribution of landscape-scale features such as availability of nesting sites and number of pollinators to understand how landscape structure, composition, and richness contribute to pollination delivery. Building from these and many other studies, Lonsdorf et al. (2009) proposed a framework to model pollination service including ecological components based on field data, nesting substrates, and floral resources (Lonsdorf et al., 2009). This approach was followed by a new model which aimed to quantify the pollination demand and supply and the match between both in the European Union (Schulp et al., 2014).

Despite the steps taken in recent years to model pollination services, getting information on pollination services and their spatial arrangement across landscapes is still problematic. In particular, there is still a lack of easy-to-use tools aiming towards a quick, yet effective method to determine the pollination delivery for at a local scale across landscapes. Therefore the aim of this study was to develop an approach with a simple user input and freely available spatial datasets, models and satellite imagery, to produce a mapped output on pollination delivery at a fine-grained resolution (300 m pixel resolution). Using this approach we can remotely obtain a landscape-scale map of the important features across landscape for pollination services. Such an approach can therefore provide a first approximation for land managers and farmers to identify potential regions to invest in actions to enhance pollination service delivery. This approach is also scalable, and can therefore be used at local to continental scales to support decision-making regionally and enable questions such as “what components of this landscape should we protect?”.

To achieve this, our model was built on the availability of crop pollinators including both wild and managed bees from six genera (*Andrena, Anthophora*, *Apis*, *Bombus*, *Megachile*, *Osmia*), the location of pollination-dependent crops, and the distance from suitable foraging habitat. Based on previous studies (Bommarco et al., 2012; Greenleaf et al., 2007; Klein et al., 2007; Lautenbach et al., 2012; Polce et al., 2013; Ricketts et al., 2008; Winfree and Kremen, 2009) we made the following assumptions in building our model:

i) For the suitable land to be classified as providing pollination ecosystem services there must be pollination-dependent cropland within the pollinator maximum foraging distance (Garibaldi et al., 2011; Greenleaf et al., 2007).

ii) The closer the nesting land cover types are to the pollination dependent crops, the greater the relative provision of pollination services will be because pollinators may be expected to forage optimally (Ricketts et al., 2008).

The overall aim of this work was to develop an approach that can be used: i) as a tool for land planners to predict consequences of different land uses on pollination services in the landscape; ii) help farmers to locate crops in places where their pollination needs are most likely to be met, and iii) to optimize conservation investments for both bee biodiversity and crop productivity. This paper describes an effective method for determination of pollination service delivery at any European parcel of land with the potential to include more or improved dataset when available. In addition, we identified which of the selected bees deliver more pollination service to European crops and which are the countries that have the highest/lowest values of pollination service delivered.

2. Methods

2.1 Pollinator-dependent crops

To determine the presence of pollinator-dependent crops for all European countries we used: the EU Corine Land Cover (CLC 2006) (The European Environment Agency (EEA), 2006) with the exception for Greece where the Global Land Cover Map for 2009 were used (GlobCover 2009) (Arino et al., 2009). The CLC 2006 and GlobCover2009 land classification were resampled to 300 m pixel size resolution.

In these landcover maps there are two classes that correspond to pollination dependent groups of crops in Europe: fruit tree and berry plantation crop (crop class 16), and complex cultivation pattern crop (crop class 20) (see Appendix A in Supporting Information). We excluded non-irrigated arable land crops, permanently irrigated land crops, and olive groves from the model because often these also contains non-pollination dependent crops such as wheat (Klein et al., 2007).

2.2 Bee pollinators: their potential distribution in Europe and richness map

To develop the potential distribution of pollinators relevant to European crops we selected twelve bee species based on Klein et al. (2007) and Garibaldi et al. (2013). These include: *Andrena flavipes, Andrena labiata, Anthophora plumipes, Apis mellifera, Bombus hortorum, Bombus lapidaries, Bombus pascuorum, Bombus terrestris, Megachile rotundata, Osmia cornifrons, Osmia cornuta, Osmia rufa/bicorni.* These bee species are known to have a wide and well-known distribution and to pollinate a broad range of crop plants (Garibaldi et al., 2013; Klein et al., 2007).

We obtained the distribution data for these twelve bees by querying the Global Biodiversity Information Facility (GBIF). In total we obtained 120429 species occurrence data points for Europe. This data was then used to build and validate distribution models using Maxent (Phillips et al. 2006). The Maxent output showed how each bee is spatially arranged across Europe.

In developing the species distribution models we used the following environmental covariates at 300 m pixel resolution: Land cover class (The European Environment Agency (EEA), 2006), elevation (Farr et al., 2007), mean annual temperature, temperature seasonality, total annual precipitation and precipitation seasonality. Climate data was obtained from Worldclim (Hijmans et al., 2005). To evaluate the model predictive performance we used the area under the curve (AUC) of the receiver operator characteristic (ROC)(Fielding and Bell, 1997). An AUC value of 0.5 indicates a random prediction (useless model), whereas the closer the value to 1, the better the predictive ability of the model (Phillips et al., 2006a). All models were validated by bootstrapping and in all cases AUC of ROC was > 0.9.

Finally, we generated a species richness map involving the twelve selected bees. This map is therefore depicting which parts of the landscape have the potential to provide suitable habitat for these pollinators.

2.3 Pollination success

The next step in building this model was to calculate which areas of Europe require pollination services; this required the determination of: pollination dependent crops, bee nesting habitats, and calculate crop-bee interactions.

The following methodology was carried out on all 12 pollinators:

i) For each pollinator, the land cover maps were reclassified into classes of crops which are pollinated by the species as defined by Klein et al. (2007) and into classes which are suitable nesting habitat for the pollinator and not nesting habitat for that pollinator (Michener, 2000) (see Table S4). The set of crops pollinated by each species was tabulated (see Table S3). We also tabulated the nesting habitats of each pollinator species according to CLC 2006 classes (see Table S2).

ii) The nesting habitats map for each pollinator was multiplied by the Maxent species' distribution map (section 2.2) to identify lands containing nesting habitats from which the pollinator potentially provides services.

iii) To account for pollination success we used distance-based approach as crude metric. The advantage of using this approach is that there is strong evidence that on average, crops 1.5 km away from areas of suitable bee nesting habitats receive only 50% of the visitation rate compared to crops adjacent to such areas (Ricketts et al., 2008). This assumption follows the work of Ricketts et al. (2008) which demonstrated that bee visitation rates declines significantly and exponentially with increasing distance from nesting sites (Ricketts et al., 2008) (see Table S1). We used this decay function to estimate relative bee foraging activity as a function of distance from nesting habitat where the higher the pollination success, the higher the value (see Table S1).

2.4 Final pollination delivery map

The final step is to calculate crop-bee interactions. To achieve this we took the values for nesting habitats, crops, and pollination success obtained for each pixel and we translated this data into a map as follows: a function for maximum foraging distance was parameterised for each species and used to calculate the maximum foraging distance for the pollinator species. A distance surface was then calculated from the map of crops potentially pollinated by the pollinator species. The resulting distance surface was normalised between 0 and 1 to allow relative pollination service provision to be compared across pollinator species, and the normalised map was multiplied by the bee' nesting habitats (point ii in section 2.3) to create the final map of relative pollination service delivery provided by nesting habitat land by the pollinator species.

The resulting maps (Fig. 3) therefore indicate the present day potential pollination delivery where the present is defined as 2006 based on the date of the Corine Land Cover maps 2006).

2.5 Pollination indexes

Within a given parcel of land, we calculated two measures of pollination service (so-called pollination indexes) with values ranging from 0 to 1; Pollination delivery index (Pdi) and the Pollination efficiency index (Pei). These indexes are obtained at every 300 m pixel resolution and can be calculated for any land parcel and/or pollinator species in Europe.

These indexes can be summarized as follows:

i) Pdi is the output of the model and express the potential pollination service across the landscape. Pdi was summarised for each bee species by calculating the mean relative pollination service provision (arithmetic mean) across Europe for each of the twelve-pollinator species. Pdi was also summarised for each country, by using zonal statistics to summarise mean Pdi.

ii) Pei is the pollination need for a specific area. Pei shows the degree of Pdi delivered in the right place (e.g. amount of pollinator-dependent crop areas in the landscape). It was calculated by dividing the Pdi by the proportion of land in crop class 16 and 20 (i.e. fruit trees and berry plantations and complex cultivation patterns, respectively) followed by a log-transformation and scaled 0-1. Pei was calculated for each country as follows:

Pei country = zonal mean Pdi country * (crop area country / total area country)

3. RESULTS

Maxent species distribution models revealed large differences between the predicted distributions of the 12 bee species (see Fig.S1). In particular, *Apis mellifera* (managed honey bee), and *Bombus hortorum* (bumblebee) displayed a wider distribution. In contrast, *Bombus terrestris* (bumblebee) and *Osmia cornuta* (Mason bee) showed relatively small range distributions (Fig. 1).

We calculated a pollination service delivery index (Pdi) at species and country level. According to our model, those bees providing more pollination service were: *Apis mellifera* (mean Pdi 0.40) together with the Hairy-footed flower bee *Anthophora pilipes* (mean Pdi 0.38) (Table 1). *Andrena flavipes* (0.35), *Osmia rufa* (Mason bee, 0.34), *Bombus lapidaries* (bumblebee, 0.34), *Bombus terrestris* (bumblebee, 0.33), and *Megachile rotundata* (Leafcutting bee, 0.32) in contrast, displayed intermediate pollination service delivery (Table 1). Finally, *Bombus pascuorum* (bumblebee, 0.07), *Andrena labiata* (0.04), and *Osmia cornifrons* (Mason bee, 0.01) displayed the lowest values <0.1 (maximum is 1). A country-by-country analysis also revealed that Denmark (0.52), Poland (0.42), and Lithuania (0.41), displayed the highest mean values of Pollination delivery index (Pdi) per unit area. In contrast, Finland (0.04), and Norway (0.02) displayed the lowest values (Table 2 and see Table S2).

Pollination efficiency index (Pei) showed that there is little relationship between the total amount of pollination service delivered at the national scale and the efficiency of service delivery to the crop areas in the different countries. For example, Norway and Spain although displaying some of the lowest Pdi values (0.02 and 0.29, respectively), displayed the highest pollination efficiencies (0.97 and 0.77; Table 2). In contrast, Denmark displayed the highest Pdi (0.52) but relatively low Pei (0.37), whereas the remaining countries display intermediate pollination efficiency indexes.

In terms of bee richness, the richness (or hotspot) map (Fig. 2) showed that the diversity of pollinators is especially high in south and central Europe: central Spain, northern France, southeastern UK, and northern Italy but relatively low in northern Europe.

4. DISCUSSION

4.1 A potential new model to quantify the provision of pollination service for European crops

In Europe alone 12% of cropland area depends on insect pollination for optimal agricultural production (Schulp et al., 2014). However, are these crops located near available habitat suitable for pollinators? Our new method deals with these questions and complements the models and tools already available (ARIES Consortium, 2014; Maes et al., 2013; Natural Capital Project). The novelty of the method presented here is summarized in three points: i) it is based on freely available data (e.g. GBIF) and not expert knowledge. In addition, there no need to collect field data for every application; ii) it provides bee richness information across the landscape, and iii) it takes into account both the delivery and demand side of the service, and moves beyond previous models by explicitly incorporating information on habitat availability, and landscape structure. Such information allows assessment of the relative importance of different parameters and changes in climate and/or landscapes for current ecosystem service delivery.

With this approach there are several modeling uncertainties and limitations. Firstly, our analysis do not account for interactions such as competition between pollinators. Although the extent to which manage honey bees are competing with native bees is debatable, some studies have shown that competition takes place with bumblebees for access to nectar (Thomson, 2004). For example, the interaction between wild and honey bees contributes more than the direct contribution of the commercial bees to the sunflower pollination (Greenleaf et al., 2006). These findings demonstrate the economic importance of interspecific interactions for ecosystem services and suggest that the protection of wild bee pollinators can help a lot the food production supply by compensating the commercial bees' scarcity (Greenleaf et al., 2006). This can promote variation in the pollination service delivery that is difficult to take into account in the model. Secondly, our model is based on presence-absence for (12) bees (not bee abundance data). This fact limits our final conclusions. To improve this aspect of the model we ideally require bee density and activity data. In particular, field data on pollinator richness and their visitation rates across European crops and habitat types. Finally, although we have used the most up to date crop map from the EU, there are limitations in classifying pollination-dependent crops. To minimize this problem we selected the two CLC types that do not include major wind pollinated crops. As a result, minor pollinated crops that are classified in the two CLC groups with the wind-pollinated crops, e.g. strawberries, are not included. But, when better land-cover maps are available we aim to incorporate them into the general modelling framework.

4.2 Pollination delivery by pollinator and country

Bees are the most important pollinator taxon (Greenleaf et al., 2007). Of the more than 16000 species described worldwide (Michener, 2000), honey bees, bumblebees, leaf cutting bees, and mason bees, have been recognized as the most efficient pollinators of a wide variety of crops (Bosch and Kemp, 2002; Garibaldi et al., 2013; Klein et al., 2009). Our analysis for 12 bees showed that due to differences in nesting habitat (see Table S3), the crops which they pollinate (see Table S4), and relative foraging activity (Table 1), these species differ widely in their pollination delivery (Table 2, see Fig. S2). For example, our model showed that the social bumblebee *Bombus hortorum* displays the highest Pdi. This might be because the ability of bumblebees to undertake large foraging distance and the availability of nesting habitats in a wide range of natural and semi-natural habitats (Greenleaf et al., 2007; Westphal et al., 2006) (see Table S1).

Our approach also allows the identification of European regions with relatively greater or lower pollination delivery index (Pdi) and pollination efficiency index (Pei). For example, Finland, Iceland, Norway, and Sweden displayed low Pdi. Such low Pdi values might be explained by low service provisioning (few pollinator species or low nesting habitat availability) or low demand (low proportion of pollinator-dependent crop areas in the landscapes). The Pollination efficiency index (Pei) distinguishes between these potential drivers. For example, despite a low Pdi, Finland has a high Pei (1). This suggests that according to the spatial structure of nesting habitats and bee species distribution, pollination service delivery to Finnish crops should be near optimal. Low Pei can still appear in these regions, but are likely to be driven by factors not related to landscape structure or bee distribution (e.g., temporal fluctuations in climate, pollinator-flowering mismatch, etc.). In contrast, some countries display relatively low pollination efficiency index values, such as Poland (0.26) and Denmark (0.37). The latter, our model suggests that here pollination service delivery may be significantly improved through landscape management to optimize habitats for bee nesting and foraging.

Our results are in line with those obtained by Lautebach et al. (2012) and Schlup et al. (2014). These authors showed that countries where agriculture contributes substantially to GDP are especially dependent on pollination (Lautenbach et al., 2012; Schulp et al., 2014). This is the case for Poland (Pdi 0.42), Germany (Pdi 0.38), and France (Pdi 0.35), where pollination is especially important in terms of GDP, and this is reflected in our Pollination delivery index. For example, according to our model, regions of Europe with high pollination service delivery such as northwestern France and northeastern of the Iberian Peninsula (Fig. 3, Table 2) represent areas which concentrate: pollination-dependent crops, suitable nesting habitats, landscape structures that ensure the presence of crops within the maximum foraging distance of pollinator nesting habitats, all within the geographic distribution of the pollinator species.

4.3 Implications at regional level

Our pollination model has already provided relevant information in: i) what extent does the current land cover type contribute to the provision of pollination service to crops, and ii) identifying potential locations for the cultivation of pollination dependent crops. However, one of the remaining aims of this paper was to deliver useful information to land managers and farmers to allow them to identify potential regions to invest and to maximise local pollinator populations and thereby optimizing pollination service delivery (Figs 2-3). Here, therefore, we aimed to complement our previous results with regional examples. To do so, we analysed a set of lower-scale maps in three regions located in Spain, Denmark, and Norway. We included these case studies as they might potentially represent the broad array of the pollination delivery provided across Europe. For example, these three examples illustrate a low, intermediate, and high pollination service delivery (Fig 3).

What it is important to highlight from these three case studies is that the model output suggests that there is a considerable heterogeneity in pollination service provision across small scales of 1 and 2 km. An important outcome from these case studies is that the transition from areas of maximum to minimum pollination provision occurs in just 1km. This fact, suggests that the availability of appropriate nesting habitats for pollinators adjacent to pollination-dependent crops is very important for farmers.

To this end, we agree with other conclusions that the introduction of green elements in agricultural landscapes to enhance nesting habitats is very important (Schulp et al., 2014). The 2020 Biodiversity Strategy also refers to the creation of green infrastructures to provide a variety of opportunities for shelter and breeding and to prevent further habitat loss and fragmentation. A recent study demonstrated for example that conserving as little as one-tenth of the nearby wild bee habitat can provide up to 40% of the pollination needs to watermelon farms (Kremen et al., 2004). Additionally, a global synthesis has found that the most important factors enhancing wild bee communities were the amount of high quality habitats surrounding farms in combination with organic management (Kennedy et al., 2013). Thus, increasing good local management practices may increase bee richness and abundance and crop production.

4.4 Opportunities and challenges for 21st century European pollination delivery

Policies that relate to ES will increasingly be mainstreamed into high-level EU policies, given the commitment to frame resource efficiency as the guiding principle of the Europe 2020 Strategy (European Commission, 2010) and to existing EU policies, including the EU common agricultural policy (CAP), aligning their objectives to the over-arching aim of “building smart, sustainable and inclusive growth for the European Union”. The inclusion of ecosystem services in these policies will mean that funding should be available from the budget currently allocated to agriculture and regional development to implement land stewardship changes that will have a positive impact on ecosystem services including pollination services. The model presented here is the starting point to discuss opportunities and challenges to build strategies important for land management and decision making in Europe. We are aware that despite the methodological advances, any study using models needs to exercise caution when deriving conclusions with relevance for policy making. However, with crop pollination by wild and managed pollinators worth some €153 billion, and the value of complete loss of such pollination services estimated to be between €190 and €310 billion (Gallai et al., 2009) it is essential that strategies for landowners are developed as a high priority, and that model systems, such as the one we present, are tested by farmers and refined by researchers as part of policy development. To be able to manage pollinators optimize and pollinations service delivery, it is important to first identify limiting factors for bee populations (e.g., landscape structure, pollinator species availability, climatic constraints), including less well-known aspects of pollination ecology (e.g. competition between managed and wild bees), and then to instigate management interventions that can increase habitat suitability and thereby the size of local bee populations. Both wild bees and honey bees provide services to crops in Europe; in setting new practices to integrate management of both honey bees and wild bees the European countries could help to enhance global crop yields.

Our main suggestions are:

i) In areas with low to intermediate pollination index, land management should be targeted to increase availability of suitable wild bee nesting habitat near and around pollinator-dependent crops to enhance pollination provisioning by wild bees. A remaining question is how to improve the Pollination efficiency index in landscapes where it is low. Our analyses showed that the spatial structure of nesting habitats and bee species distribution are important drivers for acquiring an optimal Pei and in turn, the Pdi. Future efforts to enhance pollination efficiency could be aimed at deciding upon locating crops near suitable nesting and foraging habitats and/or protecting or restoring nesting habitats near crops.

ii) Our hotspot map suggests that Nordic agricultural areas (e.g. Denmark, Finland, Iceland, Norway, and Sweden), are located outside the climatic range of many wild bee species, and here pollination service delivery may benefit from increasing the number of beehives to ensure high pollinator densities (Fig. 3). This strategy, although successful in crops such as strawberries growing in tunnels in southern Spain (Ariza et al., 2012), has several associated limitations highlighted by Garibaldi et al. (2013).

iii) Long-term crop pollination monitoring requires data to support modelling and evidence-based decision-making. To identify and implement the most efficient measures, it is necessary to have detailed knowledge of the pollination ecology and the habitat demands of the different pollinators that deliver pollination service across Europe.

This model provides an approach that can quickly obtain a first approximation for land managers to identify potential regions to invest in actions to conserve or restore nesting habitats to enhance pollination service delivery.

ACKNOWLEDGEMENTS

This research was supported by the Norwegian Academy of Science and Letters. SN is funded by the VISTA program. We thank Paul Williams, Ynghild Gilje Storhaug, and the Oxford Long-term Ecology Laboratory for helpful comments and great discussions on bee pollination.

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TABLES

Table 1. Information on the 12 bee species represented in this study and values of the Pollination delivery index (Pdi). EU: Europe. WD: Widespread.*Social bee.

Species	**Common name**	**Family**	**Distribution**	**Pdi**
Andrena flavipes	Mining bee	Andrenidae	EU	0.35
Andrena labiata	Mining bee	Andrenidae	EU	0.04
Anthophora plumipes	Hairy-Footed Flower Bee	Anthophoridae	EU	0.38
Apis mellifera*	Managed Honey bee	Apidae	WD	0.40
Bombus hortorum*	Bumble bee	Bombidae	EU	0.41
Bombus lapidaries*	Bumble bee	Bombidae	EU	0.34
Bombus pascuorum*	Bumble bee	Bombidae	EU	0.07
Bombus terrestris	Bumble bee	Bombidae	EU	0.33
Megachile rotundata	Leafcutting bee	Megachilidae	WD	0.32
Osmia cornifrons	Mason bee	Megachilidae	WD	0.34
Osmia cornuta	Mason bee	Megachilidae	EU	0.01
Osmia rufa/bicorni	Mason bee	Megachilidae	EU	0.34

Table 2. Mean pollination delivery index (mean Pdi per unit area), pollination efficiency (Pei-Pdi delivery per unit area of pollination-dependent crops), richness of species delivering pollination services (modelling probabilities), and total area of pollinator-dependent crops for a selection of countries. More details in Supplementary Information.

Country	Pdi	Pei	Pollinator richness	Crops (km^2)
Denmark	0.52	0.37	6.78	1043
France	0.35	0.55	5.17	61108
Finland	0.04	1.00	0.7	13
Germany	0.38	0.53	5.27	22671
Greece	0.30	0.60	4.47	22415
Italy	0.14	0.60	2.60	25375
Lithuania	0.41	0.45	5.87	8410
Norway	0.02	0.97	0.28	1427
Poland	0.42	0.26	5.85	15372
Spain	0.29	0.77	4.19	50618

FIGURE CAPTIONS

Figure 1. Example of species distribution models, *Apis mellifera* (a), *Bombus hortorum* (b)*, Bombus terrestris* (c), and *Osmia cornuta* (d).

Figure 2. Hotspot map showing species richness of bees delivering pollination services across Europe. Areas shown in red are predicted to have a relatively high number of pollinators contributing to pollination service delivery.

Figure 3. a) Relative pollination service delivery for Europe for complex cultivated pattern crops and fruit tree and berry plantations. Regions exhibiting b) low delivery, southern Norway; c) intermediate delivery, northeastern Spain; d) high delivery, eastern Denmark. Areas in red are predicted to deliver high levels of pollination to crops, whereas areas in dark blue deliver negligible levels of pollination service.

Figure 1

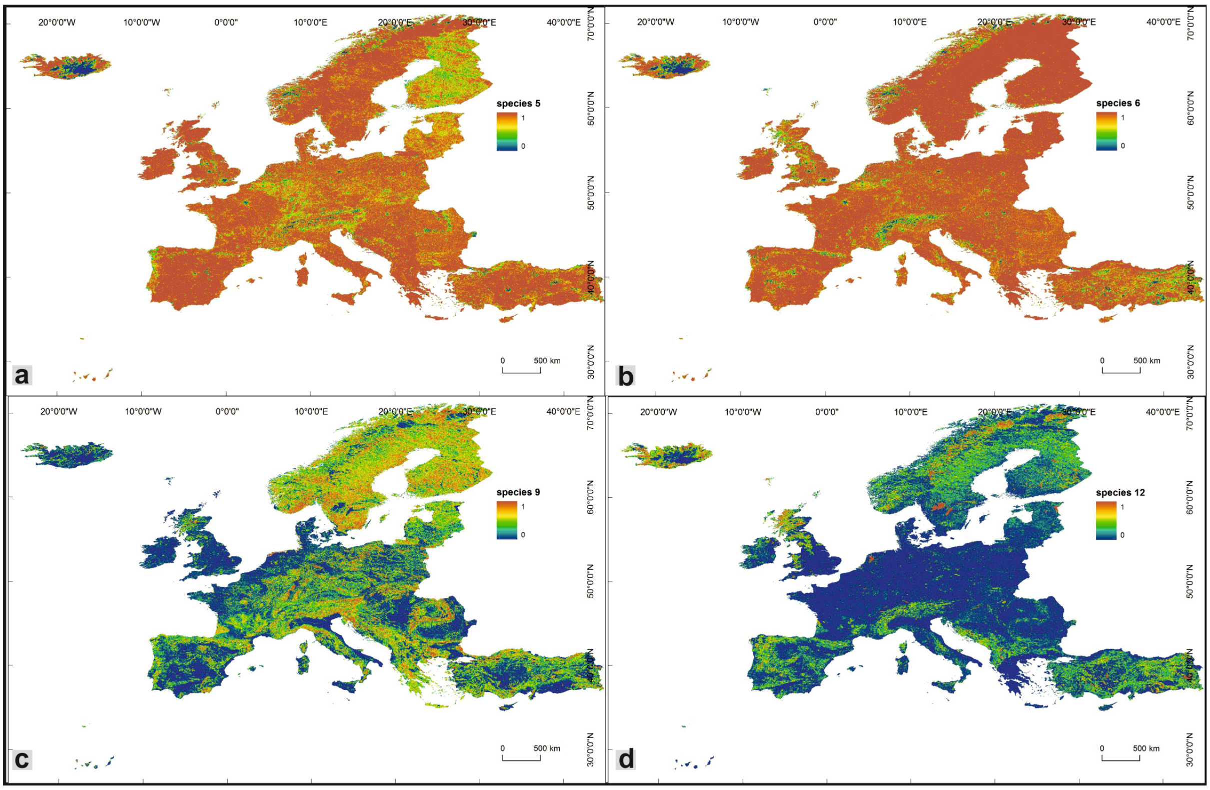

20°0'0"W
10°0'0"W
0°0'0"
10°0'0"E
20°0'0"E
30°0'0"E
40°0'0"E
70°0'0"N
60°0'0"N
50°0'0"N
40°0'0"N
30°0'0"N
species 5
species 6
species 9
species 12
1
0
0
500 km
a
b
c
d

Figure 2

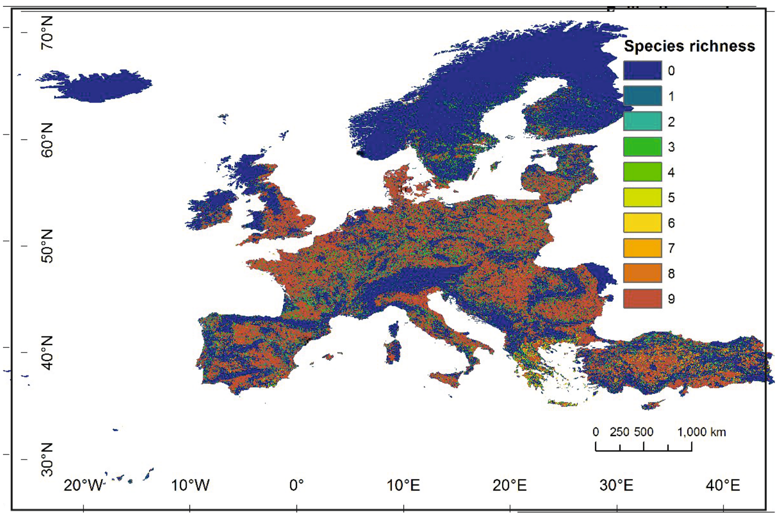
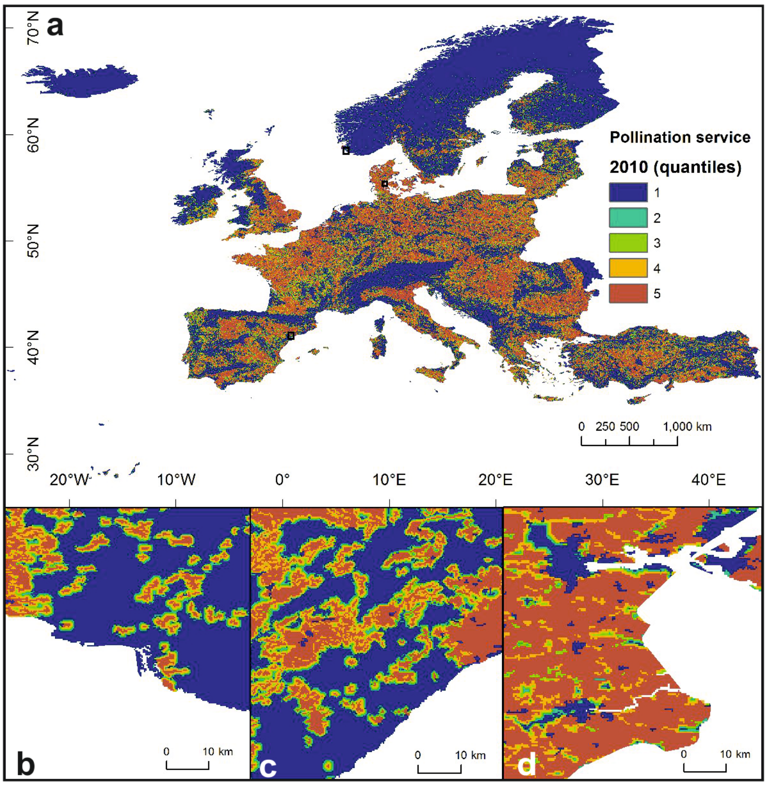

Species richness
0
1
2
3
4
5
6
7
8
9
0 250 500 1,000 km
70°N
60°N
50°N
40°N
30°N
20°W
10°W
0°
10°E
20°E
30°E
40°E

Figure 3


a
70°N
60°N
50°N
40°N
30°N
20°W
10°W
0°
10°E
20°E
30°E
40°E
Pollination service
2010 (quantiles)
1
2
3
4
5
0 250 500 1,000 km
b
0 10 km
c
0 10 km
d
0 10 km