RESEARCH ARTICLE

Assessing pollinator habitat suitability considering ecosystem condition in the Hannover Region, Germany

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Abstract

Context Habitat suitability for pollinator species is an important indicator for pollination ecosystem service potential, i.e. for biodiversity and crop provision. Modelling habitat suitability using an expert- and process-based models such as ESTIMAP-pollination is a common and accepted approach to spatially analyse pollination service potential and to make recommendations for planning.

Objectives However, the suitability as a pollinator habitat depends not only on the land use type. It is also important to consider the condition of the habitat. For this reason, ecosystem condition information was used as a parameter for ESTIMAP modelling for the first time. Ecosystem condition data was used

besides the commonly (in ESTIMAP) used information from expert assessments and from land use data.

Methods As parameters for ecosystem condition, the management intensity in agro ecosystems, the management of forests and the proportion of green space in urban areas were included and affected the modelled habitat suitability for wild bees.

Results Not all ecosystem types of the region were equally affected by the inclusion of the ecosystem condition parameter in the model. The most affected types were agricultural areas, such as arable and horticultural biotopes, whose suitability values decreased by 25.7%. As a result, areas with low suitability account for 41% of the region and 76.6% of the agro ecosystems. In forest, shrubs and woody plants land use types, the suitability decreased respectively by 4.3 and 6%. On the other hand, urban ecosystems in the city of Hannover were characterised by relatively good habitat suitabilities, especially in the proximity of wide urban forests. In 3.4% of the agricultural land, measures to support pollinators have been established. 1.6% of these measures are located in areas with low suitability.

Conclusions The results show that ecosystem condition is, in addition to land use type, an important parameter to indicate habitat suitability for pollinators. Especially for ecosystem types with varying habitat suitabilities, such as agro ecosystems, the implementation of ecosystem condition parameters is recommendable. However, the selection of suitable

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ecosystem condition indicators still requires further research and concise definitions.

Keywords ESTIMAP · Habitat suitability · Spatial data · Ecosystem condition · Mapping for policy support · Science policy interface

Introduction

Animal pollinators play a vital role as providers of pollination regulating ecosystem services in nature (IPBES 2016; Potts et al. 2017). Nearly 90% of wild plants depend to some extent on animal pollination and more than three quarters of the leading cultivated crops benefit from animal pollination. Insect pollinators support biodiversity and are fundamental for human survival (Klein et al. 2007). Wild insect pollinators are declining at a global level. No global Red List of endangered species is available for insect pollinators, but regional assessments indicate high levels of threats for bees and butterflies. In Europe, 9% of bees and butterflies species are threatened and populations were in decline by 37% for bees and 31% for butterflies (IPBES 2016). In Lower Saxony (the German federal state in which the study region is located), 62% of wild bee species are endangered and 13% of them have become extinct (Theunert 2002). This study was focused on certain wild bee species, which are described in more detail in Chapter 2.4.

Authors relate the decline of insect pollinators to a number of stressors that often act in a combined way. Stressors can be grouped in four classes: (1) land use change and intensification; (2) climate change; (3) invasion of non-native species; and (4) pest invasion and pathogens (Kluser 2007; Potts et al. 2010; IPBES 2016; Sirois-Delisle and Kerr 2018; Bennett et al. 2020; Cameron and Sadd 2020). According to the international pool of experts, that formulated recommendations to implement the standardized EU pollinator monitoring scheme (Potts et al. 2021), landscape alteration and land use changes are among the most severe pressures for pollinators. Landscape related impacts include loss and fragmentation of pollinator habitats, lower connectivity, and/or the loss of resources (food and nesting sites) (Potts et al. 2021). Bartholomée and Lavorel (2019) included land composition and configuration among the indirect landscape indicators to evaluate the pressure

of land use changes on pollinators. In addition, the intensity of land use represents a pressure for pollinators, especially in agriculture and forests. To date, various studies (Kluser 2007; Cameron and Sadd 2020; Millard et al. 2021) demonstrated that land management usually has an impact on habitat suitability for pollinators. In agro ecosystems, for instance, the type of farming system and/or the intensity of use of chemicals affect insects directly, e.g. the effect of neonicotinoids on learning, memory performance and feeding activities of honey bees (Saleem et al. 2020). Furthermore, intensive practices have indirect effects by fragmenting habitats or altering the availability of floral resources or nesting sites (IPBES 2016). In forests, that range from natural or near-natural forests to heavily modified silvicultural plantations, main sources of pressure can be caused by loss and fragmentation of pollinator habitats. Urban ecosystems, which are also heavily modified ecosystems (Maes et al. 2020), can also provide resources for pollinators. Saleem et al. (2020) conducted an experimental study in 18 cities in central Europe and found that scale-dependent factors, such as the local abundance of flowers on wild bee pollinators as well as on their pollination ecosystem services provision. In urban ecosystems the presence of green spaces is linked to the pollination service (Maes et al. 2018).

Spatial modelling of pollinator habitats and pollination ecosystem services can be a valuable tool to support policies that aim at promoting actions to halt or cope with the events or situations that causes stress to pollinators. Mapping insect or habitat distribution can support land management and help to predict the effects of the above-mentioned stressors. At the EU level, for instance, a standardized EU pollinator monitoring scheme will be implemented following the recommendations formulated by 21 international experts (Potts et al. 2020). The overall framework includes a core scheme (which contains a minimum viable scheme and complementary approaches) and additional modules, among which pollination service supply capacity is included. Pollination service supply capacity refers to the organisms responsible for the pollination function, i.e. pollinating insects, and the methods listed to monitor pollination service are all based on field work and mostly carried out by professionals (Potts, et al. 2020). Nevertheless, all methods discussed

in the report are extremely demanding in term of skills and time, and cannot been implemented in the short-term. The report also provides a selection of indirect indicators and pressure indicators that include the landscape impacts mentioned above. These indicator groups are based on variables linked to the availability of feeding and or nesting resources and can be used to build biophysical spatially explicit ecosystem services models (Bartholomée and Lavorel 2019; La Notte et al. 2017).

Several modelling approaches exist that quantify and map pollination ecosystem services. In broad terms, two key steps are needed: a map of the capacity of ecosystems to sustain the service and a map of the flow or use of the service. The first step depends on the suitability of habitats to (potentially) sustain insect pollinators (habitat suitability or capacity maps); the latter step depends on the demand for the service, namely the location of crops dependent on insect pollination (Burkhard and Maes 2017).

Habitat suitability maps depend on a set of spatially explicit data on the presence and characteristics of suitable habitats. Two commonly used approaches to derive a pollination capacity map are: Species Distribution Models (SDM) and Expert-based Models (EBM). The first is based on empirical or statistical techniques and requires species occurrence data. The suitability is then derived by relating species occurrences to habitat factors by means of statistical techniques as regression methods, machine learning techniques or Bayesian statistics (Polce et al. 2013, 2018). EBMs derive the suitability map from expert opinions and/or literature review data (Lonsdorf et al. 2008; Rahimi et al. 2009; Zulian et al. 2013a; Fernandes et al. 2020). Each land use, land cover or habitat type is scored and combined according to the capacity to provide nesting sites or foraging sites for the selected species. The complexity of EBMs depends on the number of selected spatial input parameters (e.g. nesting sites) and from the applied spatial techniques (Zulian et al. 2017).

In this study, the EBM model ESTIMAP-pollination was adapted to produce a regional scale pollination suitability map in the form of a habitat suitability map. ESTIMAP-pollination is an "advanced Look-up" approach that combines several elements of a given location that could potentially maintain nesting and foraging sites (Zulian et al. 2013a, 2017; Vallecillo et al. 2018).

The model provides a normalised 'suitability score' between 0 and 1 for each grid cell. The 'suitability' is interpreted as the 'capacity of the environment to support insect pollinators'.

The model was originally developed at the European scale (Zulian et al. 2013b, a) with the aim of assessing crop pollination ecosystem services. The approach, combined with a SDM module, was successively used for the accounting of crop pollination ecosystem services within the Knowledge Innovation Project on an Integrated system of Natural Capital and ecosystem services Accounting (KIP INCA) (Vallecillo et al. 2018).

ESTIMAP-pollination was also adapted to the local (regional and urban) scale and used in several studies (Zulian et al. 2017). In each application, the model configuration, basic components (nesting or floral availability), GIS data and parameters differ with reference to the spatial scale, the spatial context, and the policy/research question to be addressed. For instance, the Oslo municipality (Norway) was interested in modelling the distribution of habitat quality for insect pollinators as an indicator for urban general biodiversity. In a second study, the approach was used to explore the competition between wild pollinators (bumblebee and solitary bee species) and honeybees (Stange et al. 2017). In the Costa Vicentina regional Park (Portugal), pollination maps were used as communication and management tools to support local stakeholder engagement. The model was modified by adding a behavioural component that distributes pollinator visits according to flower availability (Fernandes et al. 2020). In Saxony (Germany), the model was applied to explore synergies and trade-offs of bioenergy production with other ecosystem services (e.g. production of food, fodder, erosion risk) in mixed rural landscapes (Zulian et al. 2017). In the Rio Claro region (Brasil), the model was implemented to support the development of a Payment for Ecosystem Services (PES) scheme to highlight priority areas for food security, where small farms are under pressure by sugar cane commodity (Zulian et al. 2017). Another application was developed on Terciera Island (Azorres/Portugal), where ESTIMAP pollination and INVEST pollination models were applied in parallel with the aim to test the models for their application potentials in territorial planning (https://

repositorio.ul.pt/handle/10451/36522). Rahimi et al. (2021) applied the model at the national level in Iran.

In our study, the ESTIMAP-pollination model was implemented following the protocol for model adaptation proposed by Zulian et al. (2017). The schema consists of five sections: (1) describing the decision contexts, including the application of the analysis and the final users; (2) choosing the spatial and temporal scale of the analysis; (3) building a conceptual schema consistent with steps 1 and 2 with a clear description of components and parameters; (4) data preparation; and (5) collecting stakeholder feedback. Step 5 is particularly important for EBM which depends on expert opinions. Feedback can relate also to the specific use of the results or the type of policy actions to be addressed.

Hannover region presents a variety of land types, including agricultural fields with varying crop sequences and intensities, small forests, urban and suburban areas and water bodies. Between 2019 and 2023, the German Federal Environmental Foundation DBU financed the project "ModBieN" (Spatial modelling of pollination ecosystem services in Lower Saxony for sustainable and regional landscape management). The main goal of the project was to derive recommendations for sustainable use of nature in cultural landscapes and protected areas using Lower Saxony as an example and to test the transferability of the ESTIMAP-pollination model to other regions. One of the aims of the project was to evaluate how the model results can help in planning measures, such as the creation of perennial flower strips. Perennial flower strips provide food resources and habitats for wild pollinators. Field margins can also improve the food supply throughout the year and organic farming is a resource-saving and environmentally sustainable form of agriculture that aims to promote biodiversity, protect soils and reduce climate change (BLE 2023). The work presented in this paper is part of ModBieN, which also included several rounds of stakeholder consultations to gather feedback.

This study aims to (1) adapt the ESTIMAP-pollination model to the Hannover region with its specific conditions and (2) explore how the spatially explicit information can support regional policy making and planning.

Particular attention was given to: (i) the scoring system which is a crucial element in EBMs and in this study was defined using regional expert knowledge, gathered through a web survey; (ii) the selection of suitable spatial data sets, specifically related to the distinctive features of a region; and (iii) the linkage between spatial mapping and specific policy actions that are implemented in agro ecosystems. One novelty of this approach was the introduction of an additional parameter related to the condition level of key ecosystem types (agro ecosystems, forests, urban ecosystems), which was used for the first time to further refine the evaluation of foraging and nesting suitability areas.

The results are presented at the regional level by ecosystem type (agro ecosystems, forests, urban ecosystems), using a pre-defined settlement classification (cities, towns and suburbs and rural) (EUROSTAT 2018).

Methods

Study area

The Hannover region extends across an area of 2995 km^2 in central Germany (Fig. 1a). The Hannover region is located in the south of the German federal state of Lower Saxony and forms the boundary of two larger landscapes, the Northern German Lowlands and the Lower Saxony Uplands and Hills, creating a large diversity of landscapes and biotope types that can potentially favor wild bee populations (Witt and Nußbaum 2021). Climatically, the region is located in a transition zone between the maritime climate, characterized by the North Sea in the north and the Atlantic Ocean in the west, and the continental climate of the land masses in the east, with the maritime climate dominating with prevailing westerly winds (Mlynek and Röhrbein 2010).

Based on the biotope type data of the Hannover region used in this study, agro ecosystems cover a large part (approximately 54%) of the study area and the fertile loess soils of the "Hildesheim Börde" in the southeast are one of the distinctive features of the region. Approximately 25% of the study area is covered by forests.

Urban settlements cover approximately 21% of the region, of the 21 municipalities in the Hannover
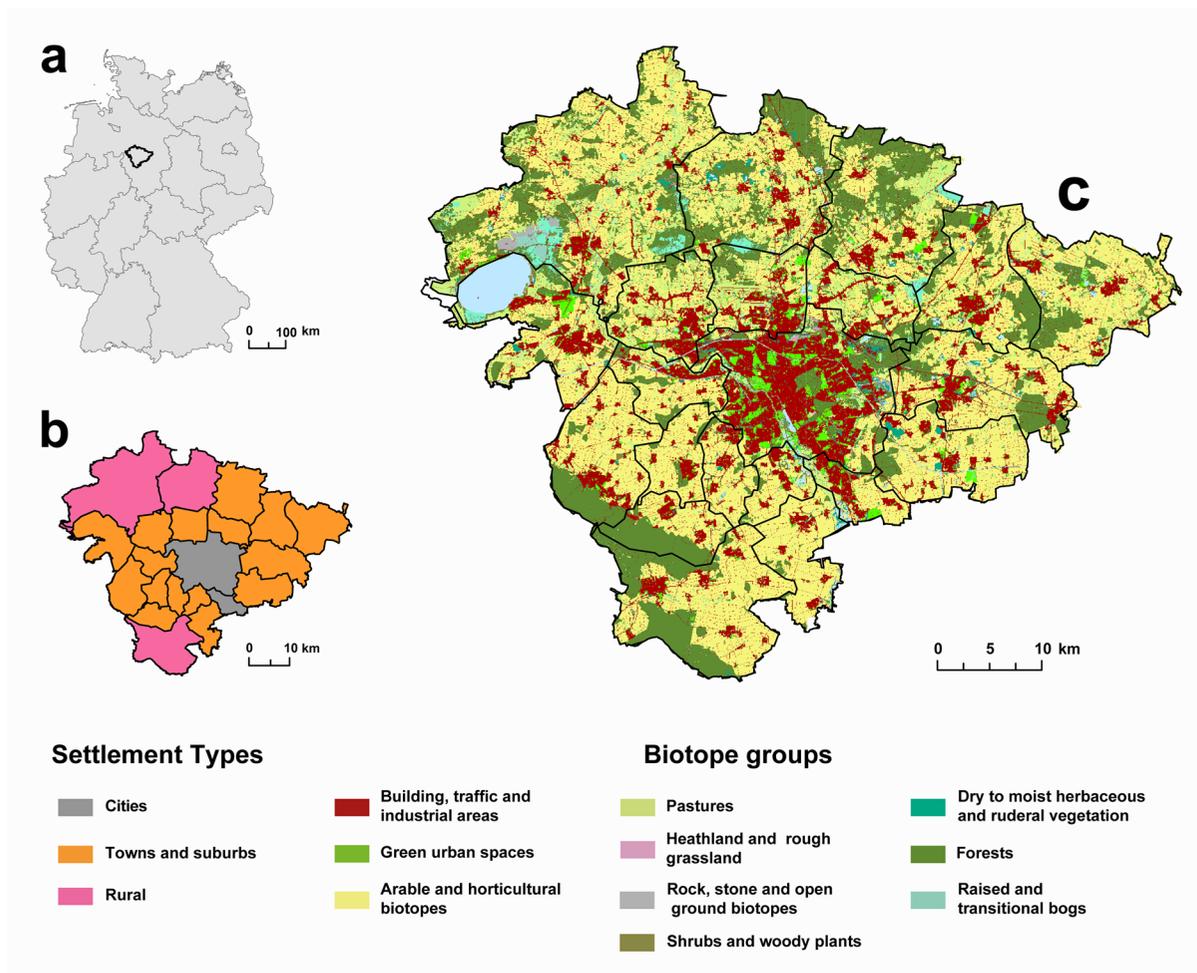
Settlement Types

- ⬛ Cities
- 🟧 Towns and suburbs
- 🟪 Rural
- ⬛ Building, traffic and industrial areas
- 🟩 Green urban spaces
- 🟨 Arable and horticultural biotopes

Biotope groups

- 🟨 Pastures
- 🟪 Heathland and rough grassland
- ⬜ Rock, stone and open ground biotopes
- 🟫 Shrubs and woody plants
- 🟩 Dry to moist herbaceous and ruderal vegetation
- 🟩 Forests
- 🟦 Raised and transitional bogs

Fig. 1 Study area within Germany (**a**), Hannover region (**b** and **c**) (© GeoBasis-DE/BKG 2018); settlement types (**b**) (Eurostat GISCO DEGURBA 2018); Main biotope groups, an intermediate classification between ecosystem types and biotope classes providing an overview of the spatial distribution of potential habitats (**c**) (Hannover Region © 2020)

region, two are classified as cities, 16 as towns and suburbs and three as rural settlements, according to the territorial classification adopted by EUROSTAT on cities (EUROSTAT 2018, Fig. 1b). The area is relatively urbanized, with a total population of 1.1 million inhabitants (estimated in 2018). 50% of the population lives in the two city municipalities (Hannover and Laatzen), located in the centre of the region and 40% is distributed in the towns and suburbs. Hannover is a medium-size town, if only the core inner city is considered, with a population of 535,932 inhabitants and is ranked 13th in terms of population number among German cities. The city is covered by 46% green and forested areas and contains

a blue network, which includes the floodplain of the river Leine (Weber et al. 2022).

The Hannover region is characterized by different ecosystem types that we distinguished in agro ecosystems, forests, urban ecosystems and semi-natural ecosystems (Fig. 1c). The region is therefore considered as an ideal study area to explore to what extent ecosystem condition can affect the suitability to support insect pollinators.

Input data

Input data used in this study (SI Table 1) were gathered at two levels: local and European. When data

were available, the most accurate local information was selected, for instance, the biotope types of the Hannover region detailed local information of actions to support pollinators; and data to derive a wild bee profile needed to score the capacity of land to support pollinators. On the other hand, to test the integration of available ecosystem condition data in the modelling approach, data at the European level were used. Ecosystem condition indicators were selected following the EU MAES approach (Mapping and Assessment of Ecosystems and their Services; Maes et al. 2020), which has become the main framework to map and assess ecosystem condition at the EU level (Vallecillo Rodriguez et al. 2022).

Biotope types

The relative habitat suitability for the wild bees modelling was based on biotope types data from the Hannover region (Hannover Region 2020). According to Blab (1993), a biotope is defined as a habitat of a biotic community (biocenosis) by a uniform composition that can be delimited in comparison to its surroundings. Vegetation is the core component of the biotope concept, so a biotope represents a recognizable section of the landscape defined for instance by characteristic vegetation type or other landscape structural or functional elements. A biotope type is the recording unit of these biotopes, which are grouped in units with similar characteristics. The biotope types of the Hannover region are based on the biotope type mapping guide (Drachenfels 2011) as well as data from the German ALK (Real Estate Cadastre) and aerial photographs. The biotope type mapping structure for Lower Saxony is organized hierarchically, with increasing detail with increasing scale. This hierarchy starts with the upper groups, followed by the main units (types) and finally the subunits (subtypes) and, if necessary, individual intermediate categories. The mapping key also contains information on the appearance, site conditions and characteristic plant communities of the respective biotope type (Drachenfels 2011).

The biotope types of the Hannover region comprise 13 superordinate groups, 127 main units (types) and 554 subunits (subtypes) as well as two categories with the designations "no information" and "other". For the ESTIMAP modelling, the level of the main unit (biotope type) was used, which showed to

be a good compromise between level of detail and standardization. However, some main units were combined into manually defined classes depending on the relevance and frequency of individual areas or biotope types. In total, therefore, the modelling was performed with 87 different units, which are referred to below as biotope classes. SI Table 2 in the supplementary information (SI) shows the original biotope types and the aggregation proposed for this study.

The 87 biotope classes were used as a base map for the pollination ecosystem services mapping. Each biotope class was scored according to the capacity to provide floral resources and nesting sites. The ratings were based on expert opinions obtained via a web survey. Ten experts from Germany who are scientifically involved with wild bees were asked about the potential nesting and foraging suitability of various biotope types. The survey was conducted by means of a questionnaire, which was sent via email. The purpose of the survey was to estimate the foraging sites availability (FA) and the nesting sites availability (NA) for each biotope class. The experts' ratings ranged from zero (no availability) to ten (highest availability). In addition, the value for each biotope class was requested in the worst case and best case. The experts were asked to evaluate the suitability of each biotope class as nesting and foraging habitat, considering the best and worst possible ecosystem condition. A scenario provides two possible scores for a given biotope class. For instance, arable land with extensive farming practices, e.g. with an establishment of buffer strips and reduced use of chemical agents, can provide nesting and foraging sites; whereas an arable land with intensive practices provide very few opportunities for pollinators. Table 1 shows examples of the different evaluations of the two scenarios for different biotope classes.

Successively, a medium case scenario was derived using the mean value of the two extreme options. This last request was extremely important because the expert estimates were then linked to the ecosystem condition level of each ecosystem type.

An ecosystem type map was created by aggregating the biotope groups. This map was used to allocate the ecosystem condition level values and to create an ecosystem condition grid, as explained in detail below.

Table 1 Example of best case and worst case scenario FA (foraging sites availability) and NA (nesting sites availability) scores of exemplary biotope classes in each biotope group

Ecosystem type	Biotope class (e.g.)	Best case (Good condition) scoring	Worst case (Bad condition) scoring
Agro ecosystem	Arable land	FA: 0.35 NA: 0.29	FA: 0.02 NA: 0.00l
Urban ecosystems	Single and row house development	FA: 0.27 NA: 0.27	FA: 0.09 NA: 0.09
Forest	Beech and alder forest	FA: 0.35 NA: 0.31	FA: 0.15 NA: 0.18

Ecosystem condition data

Ecosystem condition refers to the physical, chemical and biological condition or quality of an ecosystem at a particular point in time. Pressure refers to a human-induced process that can alter the condition of ecosystems (Maes et al. 2013).

In this study, we selected three ecosystem types that are particularly important for pollination ecosystem service supply in the Hannover region. These three ecosystem types (agro ecosystems, forest and urban ecosystems) occupy 93% of the Hannover Region. Water bodies that are not suitable as habitats occupy 3% of the area. Other ecosystem types are located on 4% of the area. The selected ecosystem condition indicators reflect the management intensity (respectively for agro ecosystems and forests) and the quantity of urban vegetation (for urban ecosystems). The selected ecosystem condition indicators are related to aspects that might cause land degradation and affect pollinators and pollinator habitats. Each input condition dataset was rescaled into good, medium or bad condition (Table 2).

Agro ecosystem condition

Agro ecosystem condition was estimated using data on the intensity of agricultural management in Europe. For our application, the land use intensity indicator developed by Rega et al. (2020) was used

Table 2 Classes extracted from the ecosystem condition datasets and the relative habitat suitability condition score class

Ecosystem type	Ecosystem group	Condition level	Habitat suitability condition score classes
Agro ecosystem	Arable and horticultural biotopes Pasture land Semi-natural areas*	Low agricultural intensity	Good condition
		Medium agricultural intensity	Medium condition
		High agricultural intensity	Bad condition
Forest	Forests Semi-natural areas*	Strict nature management	Good condition
		Close to nature management	
		Low intensity management	Medium condition
		Multifunctional management	
		Intensive management	Bad condition
		Very intensive management	
Urban ecosystem*	Settlements and other artificial Urban green spaces Semi-natural areas* Forest** Arable and horticultural biotopes** Pasture land**	Greenest Pixel: > 0.5	Good condition
		Greenest Pixel: 0.25—0.5	Medium condition
		Greenest Pixel: < 0.25	Bad condition

*semi-natural areas can be part of all ecosystem types=i.e. Heathland and rough grassland; Rock, stone and open ground biotopes; Dry to moist herbaceous and ruderal vegetation; Raised and transitional bogs

**Forest, and Arable and horticultural biotopes and Pasture land can also be inside urban ecosystems

for the evaluation of agro ecosystem condition It classifies agricultural land according to the total input intensity, calculated as the sum of energy directly consumed in farming operations plus energy consumed to produce the utilised inputs (fertilisers, pesticides, machinery, fuel). The map was reclassified in five classes using the quartiles of the energy input value in each crop system (Rega et al. 2020) and successively reduced into three classes. When intensity was low, the level of ecosystem condition was classified as good. The indicator represents a proxy of intensity of agricultural practices.

Forest condition

Forest condition was estimated according to the type of forest management intensity. Nabuurs et al. (2019) produced a European level data set, in which forested areas were classified in six intensity levels: (i) Strict nature management, (ii) Close-to-nature management, (iii) Low-intensity management, (iv) Multifunctional management, (v) Intensive management, and (vi) Very intensive management. Forest condition was estimated to be good if a forest was close to the Close-to-nature management. Similar to agricultural condition, forest condition was also divided into the classes good, medium or bad.

Urban ecosystem(s) condition

The condition of the urban ecosystems was estimated using the "greenness level", which is defined as "the amount of vegetation present in urbanised areas" (Corbane et al. 2018). Greenness is based on the pixel with the highest value of the Normalised Difference Vegetation Index (NDVI) of the year. The "greenest" values were derived from Landsat satellite image annual Top-of-Atmosphere (TOA) reflectance composites with a resolution of 30 m. Data were available at the GEE platform for the period 1996–2018 (Chander et al. 2009, Google Earth Engine Data Catalogue 2018). For this application, average data, gathered between 2016–2018, were used. Therefore, the greenest pixel of the NDVI was used, assuming that urban areas with a higher proportion of vegetation are more suitable as habitat for pollinator insects than artificial or built-up areas. Thus, areas with a higher proportion of greenery (NDVI greenest pixel > 0.5) were assigned the good

condition. The medium condition was assigned with the greenest Pixel between 0.25–0.5 and the bad condition was assigned with < 0.25.

Semi-natural ecosystem(s) condition

Semi-natural ecosystems include i.e. Heathland and rough grassland; Rock, stone and open ground biotopes; Dry to moist herbaceous and ruderal vegetation; Raised and transitional bogs.

Semi-natural ecosystems can appear in all three before-mentioned ecosystem types. In this case the values were allocated depending on the condition of surrounding ecosystems. Thus, for example, a ruderal area surrounded by intensively used agriculture also received a worst case value.

Wild bee profile

To have a reliable estimate of the nesting and food requirements of the various wild bee species present in the region and to collect expert opinions, the model was implemented using a wild bee profile as reference species. A wild bee profile can be a compromise between individual, non-representative species and a generalized average wild bee. This reference species was developed using a hierarchical agglomerative clustering approach (Bacher et al. 2010; Backhaus et al. 2018). The cluster was based on the physiological and morphological characteristics of 250 wild bee species derived from Theunert (2002); Westrich (2018); and Wiesbauer (2020). The following characteristics were examined in this cluster: (1) preferred habitat, (2) nesting mode, (3) pollen source, (4) body size (classified), (5) lifestyle, (6) flight time, and (7) phenology. The deterministic, hierarchical agglomerative cluster, with 'Average linkage' (UPGMA) was selected as cluster algorithm and the 'Dice coefficient' was chosen as proximity measure (Bacher et al. 2010; Backhaus et al. 2018). The optimal cluster solution was determined using the 'Scree test' as well as Mojena's statistical criterion. More detail on the clustering methods is available in the SI. Fig. 3 shows a section of the dendrogram from the cluster analysis. The complete dendrogram can be found in the Supplement (SI Fig. 3). Since this study is focused on the potential habitat suitability for wild bees, two generalist polylectic profiles were chosen,

which thus represent a general suitability. The species are included in the questionnaire.

This cluster analysis resulted in 56 profiles with between one and 29 species per profile. Since this study is concerned with the potential habitat suitability for wild bees, two generalist profiles were chosen, which thus represent a general suitability. The first profile is a "ground nest group" with the following description: Ground-nesting species in horizontal areas; preferably in rough pastures, meadows, dikes, bog heaths, fallows, bushes, as well as urban areas, hedges and copses. This profile includes the following wild bee species: *Andrena carantonica, A. chrysosceles, A. fucata, A. fulva, A. fulvida, A. gravida, A. haemorrhoa, A. labiata, A. nigroaenea, A. nitida, A. semilaevis, A. synadelpha, A. tibialis, A. varians, A. angustior, A. chrysopyga, A. cineraria, A. florivaga, A. helvola, A. proxima, A. floricola, A. rosae, Melitta leporina, Halictus simple*.

The second profile describes generalist wild bees that nest in structures such as plant stems and walls and includes the following descriptor: Rock and wood nests as well as in pithy stems in vertical areas; preferably gardens rich in structure, old walls, urban areas; natural rocky areas, quarries, sparse forests and forest edges. This profile includes the following wild bee species: *Colletes daviesanus, Hylaeus nigritus, H. punctulatissimun, Megachile ericetorum M. lagopoda, M pilidens, M. genalis, Osmia anthocopoides, O. adunca, O. leaiana, O.*

parietina, O. tridentata, Anthidium manicatum, A. oblongatum, A. punctatum, Heriades truncorum, Chelostoma campanularum, C. distinctum, C. rapunculi, C. florisom.

ESTIMAP-Pollination modelling

This study is based on the most recent version of ESTIMAP (Vallecillo et al. 2018). In this version, that has for instance been implemented in ecosystem accounting studies, the foraging range model (Zulian et al. 2013a) was replaced with a new module, which accounts for the effect of natural and semi-natural habitats. The module, based on the review of Garibaldi et al. (2011) and on the experimental work of Ricketts et al. (2008), implements an exponential decay function applied to the near-natural land cover classes that simulates a positive impact on pollinator species in the surrounding areas (Vallecillo et al. 2018). The exponential decay function exponentially expands the score assigned to the near-natural patches in the immediate vicinity according to the distance from the patches mentioned above. This module simulates the effect of an irregular land cover type in the immediate surrounding. The decay function is available in the Supplement (SI). Figure 2 shows a schematic structure of the ESTIMAP pollination model used in this study.
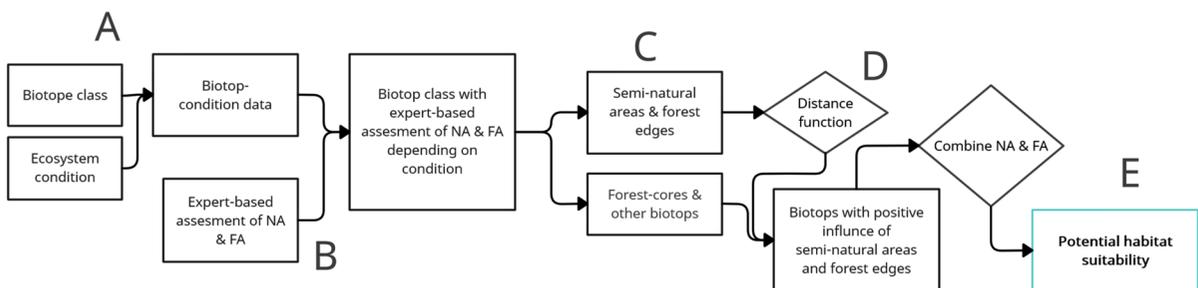

Fig. 2 Five-step ESTIMAP pollination model workflow. **A** involves the intersection of the biotope data with the ecosystem condition information to obtain an ecosystem condition scenario for each biotope class. **B** the expert assessment of NA and FA (floral and nesting) established under the good and bad scenario is linked to the biotope class-condition map. **C** specific features having a specific role to support pollinators were extracted from the biotope class and additionally prepared to model their impact on pollinator habitats (see **D**). **D** describes the application of the distance function (Ricketts et al. 2008), applied to semi-natural areas and forest edges. This affects the area in the proximity of these features. In the last **E**, NA and FA were summed and normalized. Furthermore, water bodies were set to 'No-Data'. The result is the potential habitat suitability map

Combination of biotope data and ecosystem condition

The scores provided by the experts were used to include the ecosystem condition levels in the model. Each input condition dataset was rescaled in good, medium and bad condition. In each ecosystem type and each biotope class, the suitability scores (linked to the good, medium, bad scenarios; see Table 2 for an example) were attributed according to the condition level of the prevalent ecosystem type in the specific location. This results in a final ecosystem condition grid (EC map), shown in Fig. 3.

Table 2 shows the classes extracted from the ecosystem condition data and their transformation into an ecosystem condition classification type.

Methods to analyse changes in habitat suitability due to ecosystem condition parameter

To investigate the influence of the ecosystem condition parameter, the change in modelled habitat suitability for pollinator insects was examined by calculating the difference between model results: (1) without the ecosystem condition parameter (A) and with the ecosystem condition parameter (B).

The resulting map was recoded into three classes:

- A decrease in habitat suitability
- An increase in habitat suitability
- "Equal suitability", when there was no change in habitat suitability

To avoid errors due to edge pixels, a variance of 0.01 was set for "equal suitability". This means this class has a range from -0.01 to $+0.01$.
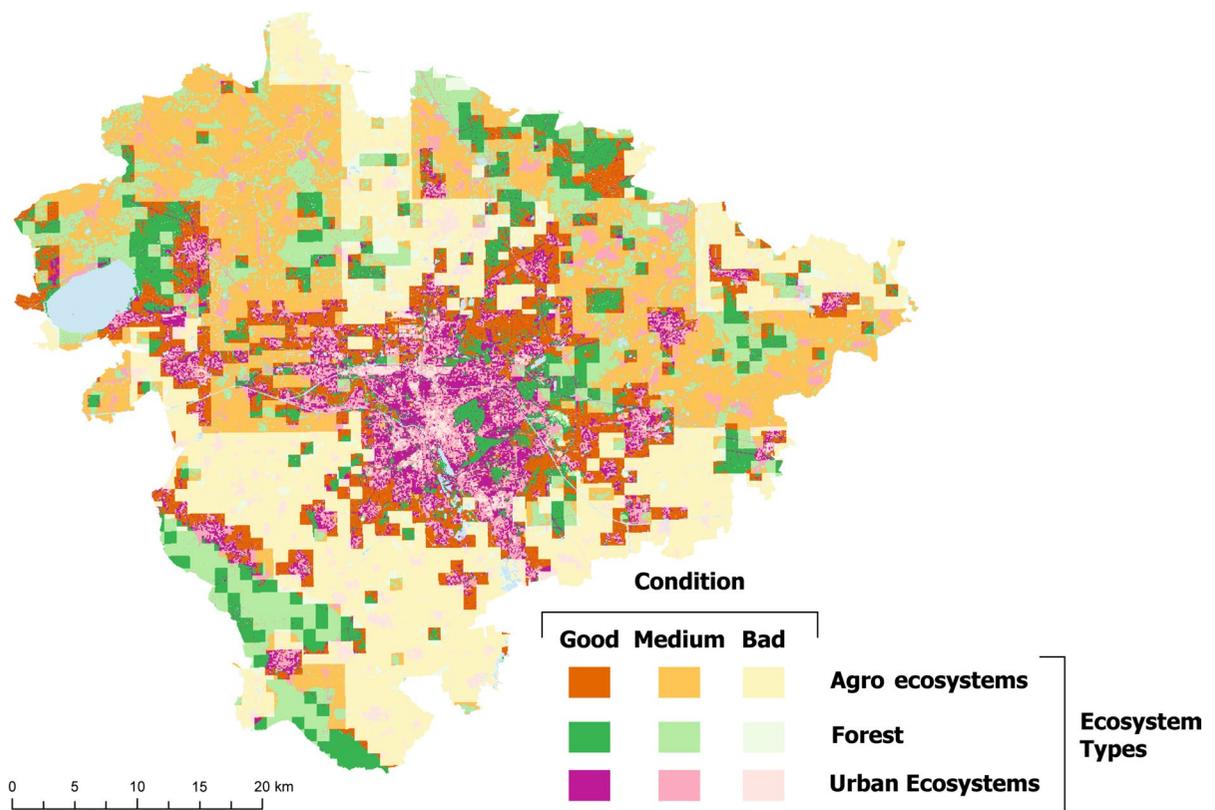
Fig. 3 Ecosystem condition map for Hannover region with cross tabulation between the ecosystem condition map and the three main ecosystem types, semi-natural ecosystems condition was valued by the condition of surrounding ecosystems (based on Google Earth Engine Data Catalogue (2018), Nabuurs et al. 2019 and Rega et al. 2020)

Values were analysed sequentially by ecosystem type and by municipalities classified by degree of urbanization (EUROSTAT 2018).

How to relate policy actions to potential habitat suitability

To investigate the role of policy actions to support pollinators, an analysis of the land shares of actions in the agricultural landscape was performed. The selection of established policy actions in the Hannover region was based on the policy actions to improve condition for pollinators included in the first IPBES thematic assessment on Pollinators, Pollination and Food Production (IPBES 2016). The complete list of actions included in the IPBES report (IPBES 2016), classified per ecosystem type, is available in SI. In this study, the types of support were selected from the InVEKOS data collected for the Hannover region (Verbraucherschutz 2022). InVEKOS data are EU-wide area-based information on the crops grown and on the measures applied for each agricultural field (Verbraucherschutz 2022). This information is provided annually by the farmers themselves.

Data were geocoded and classified as follows: 1. organic farming, 2. establishment of perennial flowering strips, 3. perennial flowering and protective strips with single sowing, and 4. perennial strips for arable wild herbs.

Since in some areas multiple actions were indicated, all types of support were coded equally to prevent double counting. In the next step, each measure on the agricultural land was assigned to the modelled habitat suitability class according to its spatial location. This was used to calculate the area of measures per habitat suitability class. Subsequently, the ratio of the measures to the total area of the agroecosystem and to the areas of the different habitat suitability classes were related and analysed.

Results

Results are reported in two steps: first, the analysis of the model outputs with and without the inclusion of the ecosystem condition parameters; second, the impact of policy actions for pollinators support already established in the study area.

The adaptation of ESTIMAP in the Hannover region: the habitat suitability maps

The habitat suitability maps were rescaled in 5 value classes with equal intervals: very low (<0.2); low (0.2–0.4); medium (0.4–0.6) high (0.6–0.8) and very high (>0.8).

With the implementation of the basic ESTIMAP-P procedure, most of the study area (93%) was rated with habitat suitability between 0.2 and 0.6, as shown in Fig. 4A. These values characterize mostly agricultural areas and forests. This range was divided into 51% with a rating between 0.2 and 0.4 (low suitability) and 42% with a rating of 0.4 to 0.6 (medium suitability). Values below 0.2 (very low suitability) was found in only 2% of the landscape. Values above 0.6 were present in 5% of the landscape. The general distribution of the modelled habitat suitability was therefore rather homogeneous. Spatially, the areas with a rating above 0.6 are mostly located near the city of Hannover.

When the ecosystem condition parameter was included in the modelling (Fig. 4 B), 94% of the study area was rated with a habitat suitability between 0.0 and 0.6. This value breaks down into 22% with a score between 0.0 and 0.2 (very low suitability), 44% with a score of 0.2–0.4 (low suitability), and 28% with a score of 0.4 to 0.6 (medium suitability). For the most part, agricultural areas achieved a rating between 0.0 and 0.4 and forests received a rating between 0.2 and 0.6. Scores above 0.6 were found in 5% of the landscape. Thus, the overall distribution of habitat suitability was, as could be expected, more heterogeneous than without taking ecosystem condition into account.

Spatially, the areas with a rating above 0.6 were still located near the city of Hannover. However, the study area showed a homogeneous distribution of suitability values. Table 3 presents the median values of habitat suitability, without and with the implementation of ecosystem condition, by ecosystem type and biotope group. The introduction of the ecosystem condition parameter has reduced the median habitat suitability score in all biotope groups except urban green spaces, rock, stone and open ground biotopes and raised and transitional bog. Habitat suitability values decreased the most in arable and horticultural biotopes (-25.7%); settlements and artificial (-14.2%) and dry to moist herbaceous and ruderal
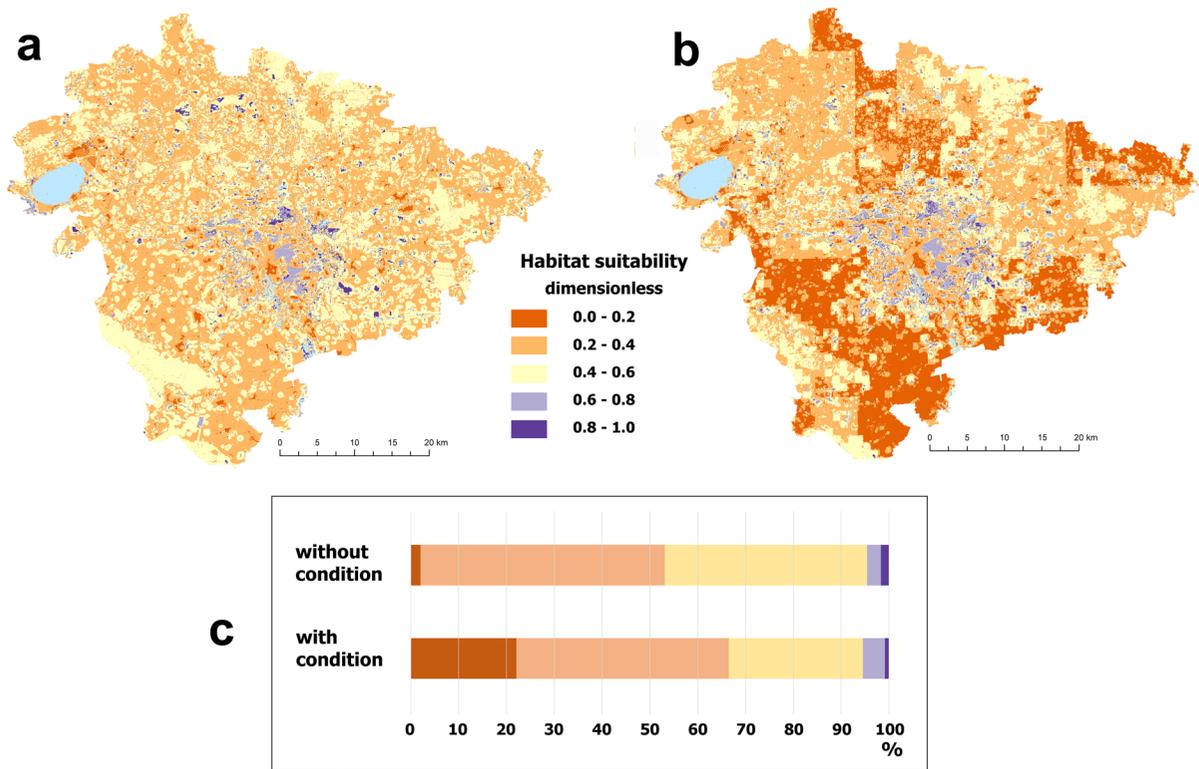
Fig. 4 Ecosystem condition map, cross tabulation between the ecosystem condition map and the three main ecosystem types. **A** no ecosystem condition parameters were implemented; **B** ecosystem condition parameters were implemented; **C** distribution of the suitability classes with and without the ecosystem condition parameter (%)

Table 3 Habitat suitability (calculated with and without ecosystem condition parameters) by biotope type group. Median values are reported

Ecosystem type	Biotope group	Habitat suitability score (median)	
		without ecosystem condition	with ecosystem condition
Agro ecosystem	Arable and horticultural biotopes	0.35	0.26
	Pasture land	0.38	0.34
Urban ecosystems	Settlements and other artificial surfaces	0.35	0.30
	Urban green spaces	0.49	0.51
Forest	Forests	0.46	0.44
	Shrubs and woody plants	0.50	0.47
Forest/agro/urbanecosystems (semi-natural areas)*	Heathland and rough grassland	0.82	0.80
	Rock, stone and open ground biotopes	0.17	0.21
	Dry to moist herbaceous and ruderal vegetation	0.82	0.72
	Raised and transitional bogs	0.24	0.25

*Semi-natural areas can be part of all ecosystem types

vegetation (− 12.2%). On the contrary, values of habitat suitability increased in rock, stone and open ground biotopes (23.5%) and urban green spaces (4.08%).

This result was confirmed by the spatial analyses conducted on the one side considering the difference between habitat suitability computed without and with ecosystem condition parameters and, on the other side, focusing on the distribution of habitat suitability computed with the ecosystem condition parameter.

Figure 5 shows (a) the difference between the habitat suitability score computed without and with ecosystem condition parameters, per ecosystem type (from now on called change) and (b) the share of land characterized by the three directions of change (increased, equal, decreased). The analysis revealed that a reduction in the suitability score occurred in all ecosystem types. Nevertheless, in forests and urban ecosystems, we detected a similar distribution of the three categories with a slightly higher share

of land where a decrease of the scores occurred (respectively 55.6% in urban ecosystems and 60.9% in forests) and one third of the land denoted an increase of the scores (36.2% in forest and 37.1% in urban). On the contrary, agro ecosystems were characterized by a prevalence of land with a decreased habitat suitability score (78.8%).

In agro ecosystems (that cover 54% of the region), only 1% of the land maintained the an equal suitability score, on the contrary 79% of the land was affected by a decrease in the habitat suitability and 20% by an increase of habitat suitability. This includes all areas that can be assigned to agroecosystems. In forests, only in 3% of the land the suitability was equal. Lowest suitability linked to ecosystem condition was computed in 61% of the forest land (15% of the total area) and an increased value characterized 36% of the forest areas. In settlements (31% of the total area), an equal score was maintained in 7% of the land, 56% of the land was characterized by a decrease in the habitat
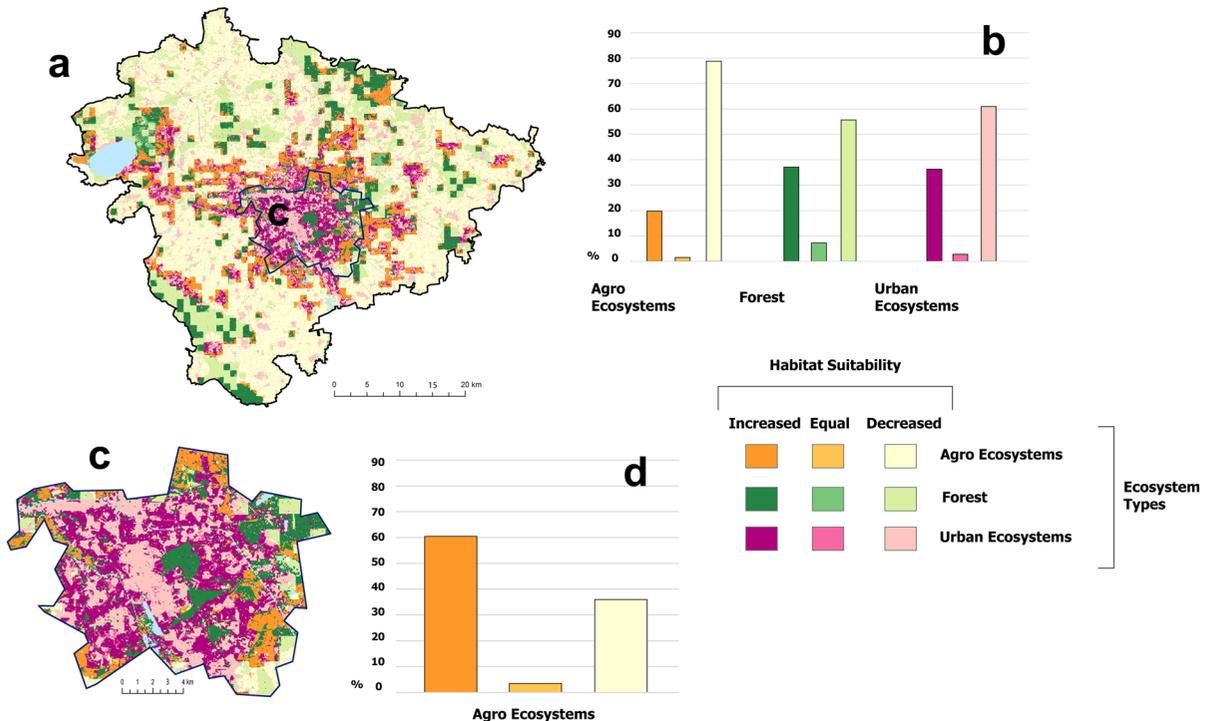

Fig. 5 a Direction of change in habitat suitability computed without and with ecosystem condition parameters per ecosystem type in the whole region, **b** direction of change in habitat suitability, share in each ecosystem type **c** direction of change in habitat suitability computed without and with ecosystem condition parameters per ecosystem type in the city of Hannover, **d** direction of change in habitat suitability, share in agro ecosystems in the city of Hannover

suitability and 37% registered an increase in the suitability score.

In 60% of the land within the City of Hannover, the introduction of the ecosystem condition parameter increased the suitability score; and 36% of the area showed decreased values.

The change in habitat suitability per settlement type confirms that rural settlements, towns and suburban areas predominantly show a decrease in habitat suitability when condition data are included in the model, respectively in 81% of rural settlements and 68% of towns and suburban areas. In cities, the habitat suitability improved in 56% of the land (Fig. 6).

The spatial distribution of the habitat suitability, computed with the ecosystem condition parameter, is presented in Fig. 7. Most part of the study area was covered by agro ecosystems with a low or very low habitat suitability (<0.4; 41.58%). Forest and semi-natural areas with a low or very low (<0.4) habitat suitability covered 22.1% of the land and settlements with a low or very low (<0.4) habitat suitability covered 15.6% of the area.

Figure 8 shows the results per settlement types. Most part of the area (61.5%) was covered by not or

moderately densely populated settlements (classified as rural or as towns/suburban areas) characterized by a low or very low habitat suitability score (<0.4). Respectively 38.6% of the areas with low and very low scores were in towns/suburbs and 22.8% in rural settlements.

Analysis of policy actions per agro ecosystem and habitat suitability class

The actions to support pollinator habitats that have been established in the Hannover region cover 3.4% of agro ecosystems. In this study, these actions selected for analysis consist of perennial flowering strips and field marginal herbs and organic farming. Results from the cross-tabulation between areas with established measures in agro ecosystems (classified by habitat suitability level) are presented in Fig. 9.

Figure 9 A shows the proportion of areas (%) with measures, calculated for each habitat suitability class (bar charts) for the all agro ecosystems (red).

The highest proportion of areas with measures (4%) was located in areas with the habitat suitability
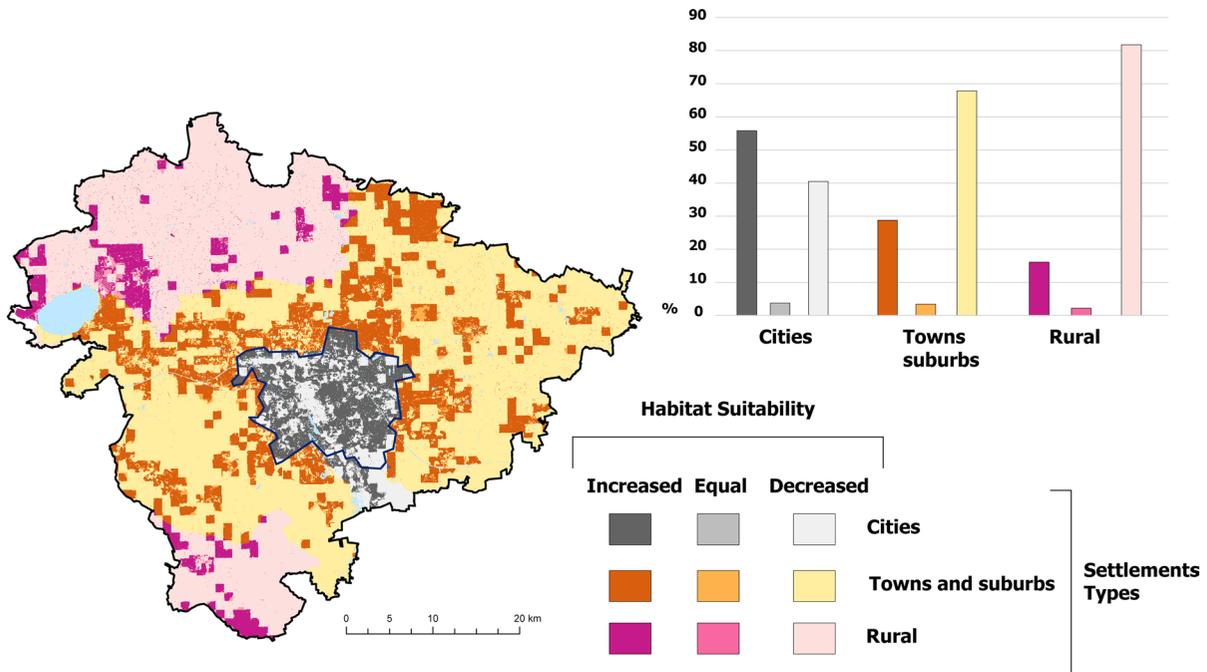
Fig. 6 Difference between habitat suitability scores computed without and with ecosystem condition parameters in habitat suitability per settlement class, direction of change in habitat suitability, share per settlement class
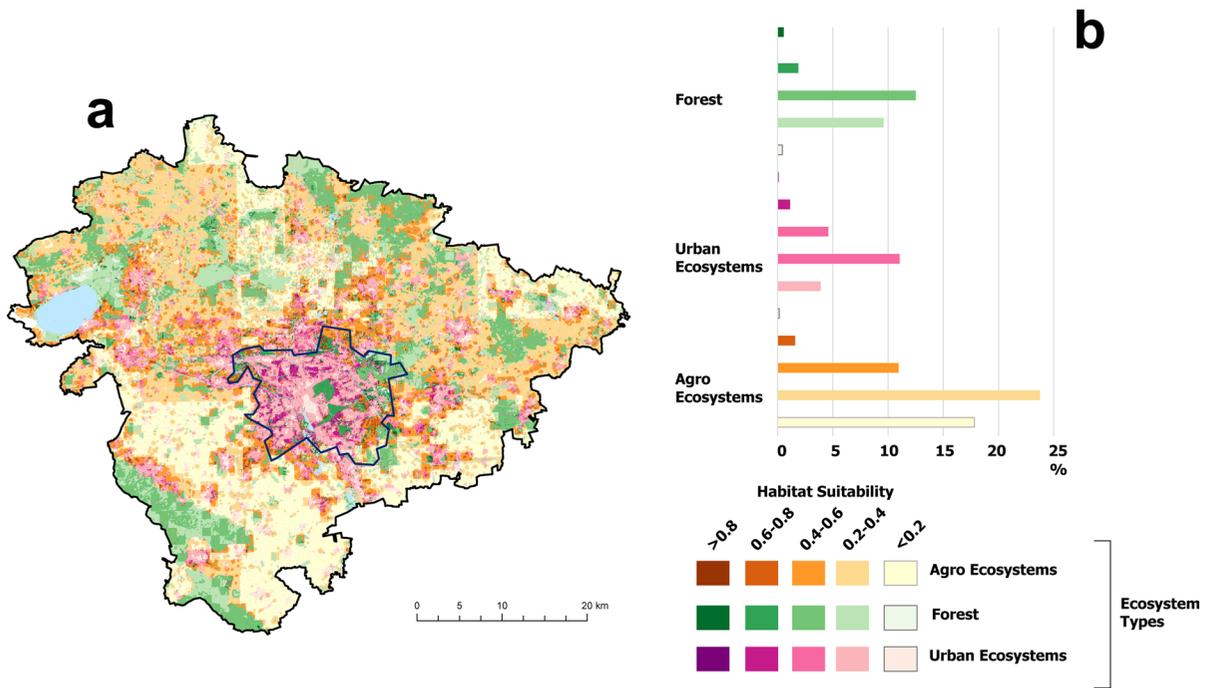
Fig. 7 a Habitat suitability with ecosystem condition per ecosystem type, **b** share of habitat suitability class per ecosystem type
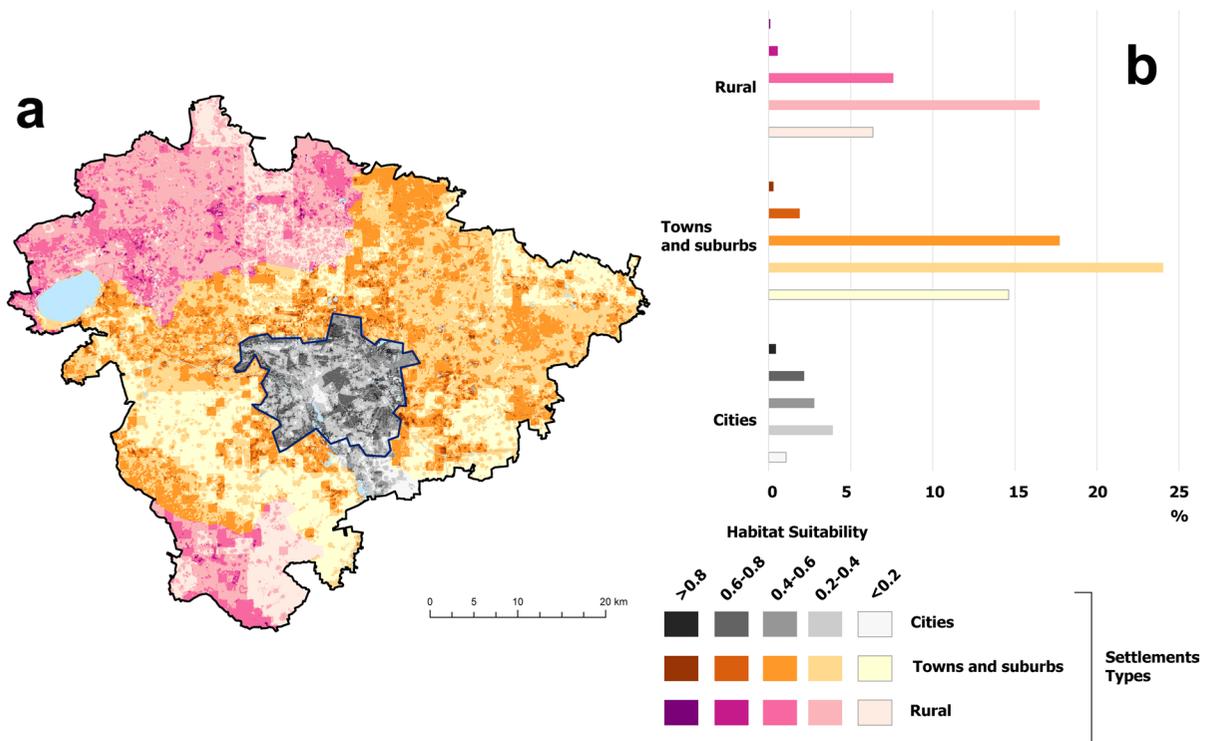

Fig. 8 a Habitat suitability with ecosystem condition per class for degree of urbanization, **b** share of habitat suitability class per settlement types
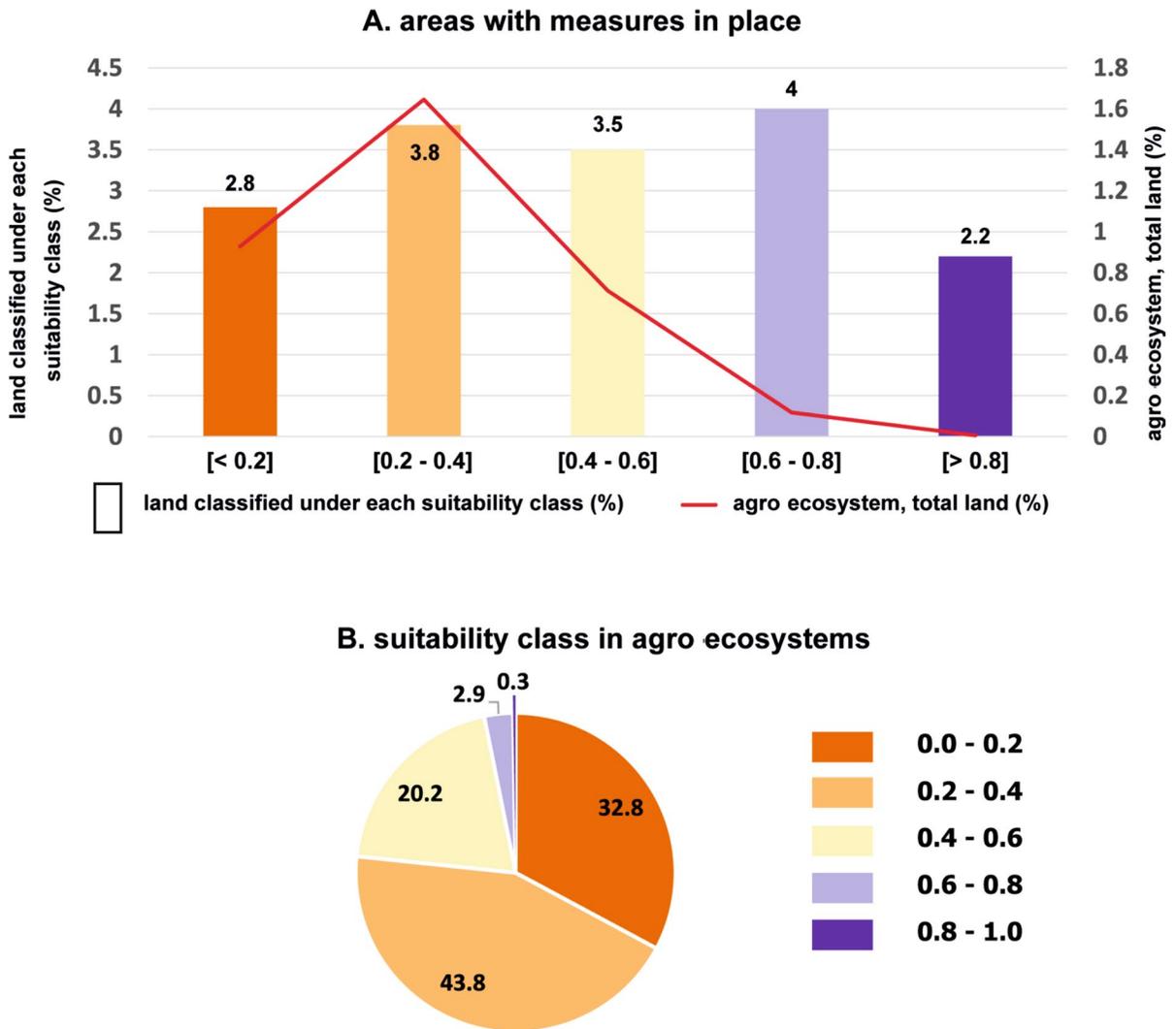
A. areas with measures in place

B. suitability class in agro ecosystems

Fig. 9 **A** Areas with defined measures, proportion of area calculated with reference to the areas classified in each habitat suitability class, with bar charts for the different habitat suitability classes (blue bar chart as legend symbol) and a red line chart for the proportion of all agro ecosystems **B** Share of land computed with reference to agro ecosystem classified under each habitat suitability class (based on Verbraucherschutz 2022)

class 0.6–0.8; however, this area represents 0.2% of the total area of agro ecosystems.

The next lower proportion of areas with measures (3.8%) was in areas with the habitat suitability class 0.2–0.4, which represents 1.6% of the total area of agro ecosystems.

The next ranked value of area shares with measures (3.5%) was in areas of the habitat suitability class 0.4–0.6; which is 0.7% of the total area of agro-ecosystems. In areas of the habitat suitability class 0.0–0.2, there were 2.8%; representing about 0.9% of

the total area of agro ecosystems. The lowest proportion of areas with measures and the lowest proportion of the total agro ecosystem area was located in areas with the highest habitat suitability (0.8–1.0).

Figure 9 B presents the share of habitat suitability classes in the total area of agro ecosystems of the region. The largest share with 43.8% was in the second lowest habitat suitability class (0.2–0.4), proportionally followed by the lowest habitat suitability class (0.0–0.2) with 32.8%. The next highest proportion (20.2%) was in the habitat

suitability class 0.4–0.6. The two highest habitat suitability classes (0.6–0.8 and 0.8–1.0) had a combined area proportion of 3.2%. Whereas the highest habitat suitability was represented in only 0.3% of the area in the agro ecosystem.

Discussion

ESTIMAP-pollination with ecosystem condition parameter in the Hannover region

From a spatially explicit perspective, the implementation of the ecosystem condition parameters increased the heterogeneity in the resulting habitat suitability map. This was reflected by the fact that not only the definition of the biotope type, group or ecosystem type are important, but also its condition and the areas in the proximity. Thus, for instance, a farmland can be evaluated not only in regard to the compositional diversity and spatial configuration of landscape elements (Wu, 2008), but also in regard to the type of management. Management measures were used as a proxy for ecosystem condition in this assessment, thus indicating the resulting damage through or support of the respective measures for insects (Klein et al. 2006).

This study also showed that the modelled habitat suitability was not equally affected by the ecosystem condition indicators in all ecosystem types and that the type of selected indicators is extremely important. In the study area, the influence of integration of the ecosystem condition indicator has been particularly noticeable on agro ecosystems; where the range between good and poor suitability was widest.

The inclusion of ecosystem condition allowed to identify the zones where a bad case scenario could occur and where further policy actions would be beneficial to transform the landscape and improve pollinator habitat suitability.

The use of the ecosystem condition parameter reduced the median habitat suitability score in all biotope groups except urban green spaces. This makes sense, mainly because of the nature of the parameter used in urban ecosystems, that focused only on urban vegetation. Nevertheless, areas rated with scores from 0.8 to 1 are located, in both suitability maps, near to the city of Hannover. The city is one of the greenest in Germany (46% of the municipality is covered by urban green spaces) and contains, for instance, the "Eilenriede".

The results of the suitability map calculated using the ecosystem condition parameter show that most of the area with a habitat suitability low and very low (<0.4) is covered by agro ecosystems (41.58% of the total area). This means that almost half of the agro ecosystems do not provide habitats suitable to pollinators and could benefit from actions to improve the situation. This is explained by the fact that agriculture is usually conducted intensively. Only about 5,2% of agriculture in the region is classified as organic (Verbraucherschutz 2022). This is particularly evident in the southern areas, where the most fertile and thus also the most productive soils are located. This high natural productivity generally leads to intensive farming and a low proportion of land used for measures to promote habitats suitable for insects.

The results of the suitability map in regard to settlement types show that areas with very low and low values were mainly located inside towns and suburban areas (38.6%). Towns and suburban areas are intermediately densely populated areas, where less than 50% of the population lives in an a urban centre, but at least 50% of the population lives in a semi-dense area (or urban cluster) (EUROSTAT 2018). They are not densely urbanized and are covered also by agriculture and forests, as demonstrated by an analysis conducted at the EU level, where towns and suburbs are covered by 41% of agricultural areas and 30.6% of forests (Zulian et al. 2021).

From our analysis, we could derive that in 67.8% of the land inside towns and suburban areas, a decrease in habitat suitability occurred when considering ecosystem condition. This affects mainly agricultural and forest lands. The use of ecosystem condition data in the model revealed interesting results not only in rural areas but also in more urbanized land. The approach allows to unravel the dynamics in towns and suburbs, where most of the agricultural land in bad condition is located, and cities where, on the contrary, the use of the ecosystem condition map allowed to detect 55% of land with an increased suitability value. This means that the method can support policy measures in different types of settlements and ecosystems by identifying areas where habitat suitability needs to be improved or where it potentially has a higher benefit. This benefit can be, for example, the improvement of the biotope

network. Particularly interesting is the focus on the management of agriculture in urban and peri-urban areas or the measures to increase habitat suitability in private gardens, public urban parks or small remnant green patches located within the cities.

Analyses of policy actions

The analysis of established policy actions showed that three out of four actions are based on the implementation of measures related to extensive agriculture. For example, uncultivated patches of vegetation such as field margins with extended flowering periods are created and farmers are rewarded for implementing pollinator-friendly practices. This is intended to address immediate risks of pollinator decline. In fact, these strategies are recommended as successful actions to improve current conditions for pollinators (IPBES 2016 p. 43 Table 1) Furthermore, diversified farming systems are supported. This is to promote ecologically-oriented agriculture through active management of ecosystem services. A broad action is to support organic farming systems, diversified farming systems and food security. This involves the strengthening of existing diversified farming systems. In 3.4% of agro ecosystems established measures are applied and most of them characterize areas with low habitat suitability (1.6%). It would be interesting to use ESTIMAP in the future to monitor the areas with established measures and verify changes.

Conclusions

The adaptation of ESTIMAP-P by using the ecosystem condition parameter in the Hannover region provided interesting and useful results, not only by revealing the areas with low levels of habitat suitability, but also providing information that might help implement the most effective interventions. The model is in fact an interesting and suitable spatially explicit tool to identify areas where measures are needed and to monitor their implementation. The use of an additional parameter linked to ecosystem condition increased the spatial heterogeneity of the modelled map of habitat suitability for wild bees. Nevertheless, more work is needed from a methodological perspective. On the one hand, the

ecosystem condition indicators that were selected for this study as proxies are not exhaustive and they were not originally calculated at the local level.

In agro ecosystems and forests particularly, more effort is needed to fit the ecosystem condition data to the specific characteristics of a region. In agro ecosystems it would also be important to include additional information related, for instance, to the use of pesticides or to other specific local management practices that might affect insect pollinators. In urban ecosystems, which are recognised as important habitats for pollinators, more data should be included in order to comprehensively evaluate ecosystem condition and related pollination regulating ecosystem service supply. For instance, it would be interesting to link the habitat suitability to the share of sealed land (Biella et al. 2022), to the type of management practices established in public parks and private gardens (Goddard et al. 2010; Tonietto et al. 2011) and to the presence of other species in conflict with local pollinators (Stange et al. 2017). In summary, the novel implementation of an ecosystem condition parameter for key ecosystem types proved to enhance the model outcomes and the application potential for sustainable landscape management. Future work is foreseen to develop local indicators able to provide a complete overview of key ecosystems condition, specifically designed to evaluate suitability for pollinators.

Data availability   The data produced in this study are available upon request. The original data of this study must be requested from the appropriate institutions.

Declarations

Competing interests   The authors declare no conflict of interest.

Ethical approval   Not applicable.

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