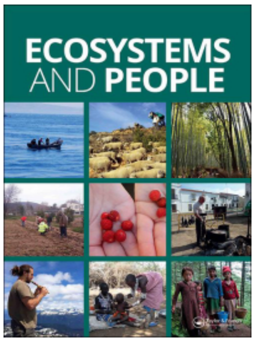

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RESEARCH

Coupling spatial pollination supply models with local demand mapping to support collaborative management of ecosystem services

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ABSTRACT
Mapping of ecosystem services (ES) is a powerful tool for communication and knowledge sharing about the implications of ecosystem management practices for human wellbeing. This research aimed to show the usefulness of ES mapping for decision-making by combining modelling of ES supply with ES demand mapping in a participatory process with the engagement of relevant stakeholders. We used the ESTIMAP-pollination model to map wild bee abundance and pollination supply in the Sudoeste Alentejano and Costa Vicentina Natural Park (PNSACV) in Portugal. The model was modified by adding a behavioural component that distributes pollinator visits according to floral availability. Balancing pollination supply with crop dependency levels allowed visualising potential areas of satisfied and unsatisfied demand and testing the effectiveness of ecosystem management interventions. The discussion of these results in two participatory workshops triggered the first collective debate about pollination in the PNSACV. This engagement enabled the development of a shared understanding about this ES and highlighted the role of ES maps as tools to support collaborative natural resources management.

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KEYWORDS
Pollination ecosystem service; ES modelling; ES mapping; ES supply and demand; stakeholder engagement; participatory workshops

1. Introduction

1.1. *Biotic pollination ecosystem service*

The ecosystem services (ES) concept has been promoted as a language capable of linking scientific research and decision-making to address landscape planning and environmental management issues (Granek et al. 2010; Braat and de Groot 2012; Jordan and Russel 2014; Dick et al. 2018). Biotic pollination is often used as an example to illustrate the link between ecosystem functioning and human wellbeing that underpins the concept of ES (Hanley et al. 2015). Plant–pollinator relationships are critical to ecosystem functioning, as most wild and cultivated flowering species depend, at different extents, on pollinator visits to set seed and reproduce (Kevan 1999; Ollerton et al. 2011). Such interactions contribute to the increase in yield, stability and quality of an array of crops (Klein et al. 2007; Garratt et al. 2014), which includes fruits and vegetables, that provide essential nutrients to healthy diets (Eilers et al. 2011; Chaplin-Kramer et al. 2014). Pollinator-dependent wild plant communities contribute to landscape aesthetics and sense of place, delivery of food and shelter resources to different species and processes that support other ES (e.g. pest control, soil protection) (Wratten et al. 2012).

Both wild and managed bee species play an important role in crop pollination. Farmers often rely on managed honeybees (*Apis mellifera*) hives or purchased bumblebee colonies to ensure crop pollination (IPBES 2016). However, a wild pollinator assemblage near an agricultural field increases crop yield more efficiently than a single managed species (Garibaldi et al. 2013; Woodcock et al. 2013; Kleijn et al. 2015). Furthermore, total reliance on managed species carries a risk due to contamination by pesticides and diseases that are causing colony losses.

Although there is a lack of data regarding wild pollinator occurrence and distribution in many geographical regions, regional declines have been documented (IPBES 2016), attributed to the combined effects of agricultural intensification, landscape fragmentation and habitat loss, climate change, alien species and pathogen transmissions from managed species (Kremen et al. 2002, 2007; Kuldna et al. 2009; Potts et al. 2010). Evidence of a global pollinator decline, coupled with an increasing demand for agricultural products has triggered the attention of policymakers upon the consequences of pollination deficits on human welfare (Potts et al. 2010; IPBES 2016).

Communicating both ecological and socioeconomic dimensions of this issue through the ES approach can help resource managers, farmers and

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other stakeholders in formulating pollinator conservation policies and identifying measures to ensure the perpetuity of the pollination ecosystem service (Ratamäki et al. 2015; Narjes and Lippert 2016). Knowledge on trends in pollinator abundance and their spatial distribution, and about the impacts of land management options, agricultural practices and farmers' behaviour is needed to demonstrate the value of wild pollination and to support the design of policy instruments, such as agri-environmental measures, to promote pollinator habitat conservation and to motivate farmers to adopt measures in their fields (IPBES 2016).

1.2. Mapping ES supply and demand

Mapping of ES has been advocated as a powerful platform to support the articulation of this knowledge in landscape planning and natural resources management (European Commission 2011; Burkhard et al. 2013; Maes et al. 2016). Maps provide a spatial representation of ES indicators, highlighting those areas with a higher contribution to ES provision (ES hotspots) and others where ecosystems are threatened (Hauck et al. 2013; García-Nieto et al. 2013; Schröter et al. 2015).

Additionally, maps of ES can be used to initiate and facilitate dialogues between stakeholders by identifying service provisioning areas and illustrating potential spatial and temporal mismatches between ES supply and demand (Bagstad et al. 2013; Geijzendorffer et al. 2015). However, the practical application of ES maps to support decision-making processes is still below expectations (Albert et al. 2014; Cowell and Lennon 2014; Posner et al. 2016a, 2016b). 2016a, b

Particularly regarding pollination service supply mapping, current approaches rely mostly on phenomenological spatial models based on proxy indicators due to a lack of empirical data of species distribution and abundance in most regions (IPBES 2016; Lavorel et al. 2017). Demand for pollination can be mapped according to the spatial distribution of crops and dependency levels (Lautenbach et al. 2012) supported by yield analysis experiments and literature review.

Few published attempts to map mismatches between supply and demand levels are described and only at continental scales (Serna-Chavez et al. 2014; Schulp et al. 2014b; Koh et al. 2016). While these large spatial scale analyses provide useful insights on potential regional deficits, they are less suitable to inform local management needs, as aggregated maps fail to capture the local nature of the service flow between nesting habitats and crops, given the limited distances reached by pollinators (Hauck et al. 2013). This analysis is widely limited by: (i) the use of aggregate and often outdated land use and cropland datasets, as fine-scale spatially explicit data are rarely available (Zulian et al. 2013a; Schulp et al. 2014b), (ii) a lack of consideration of behaviour mechanisms describing pollinators foraging activity in pollination service supply models (Olsson et al. 2015); and (iii) yield dependency levels are only assessed on a limited set of case studies (Melathopoulos et al. 2015). Local stakeholders may provide relevant knowledge to overcome some of these information gaps.

1.3. Stakeholder engagement in ES mapping

The need for a stronger consideration of stakeholder engagement during ES mapping as a source of local knowledge and to enhance acceptance of the results has been acknowledged (Cowling et al. 2008; Hauck et al. 2013; Fagerholm et al. 2016; Willcock et al. 2016). Local stakeholders' perceptions and knowledge are relevant information that complements biophysical mapping (Palomo et al. 2013, 2014). Furthermore, it is important to assess how stakeholders perceive maps and how they may be improved to become more robust and effective planning tools (Hauck et al. 2013). The use of maps in a participatory context with the engagement of different stakeholder groups (e.g. environmental managers, farmers, land-use planners) may provide a common platform to support interaction and exchange of viewpoints, thus contributing to solve conflicts between different interest groups regarding natural resources management.

1.4. Research objectives

This research aims to illustrate and enhance the usefulness of pollination ecosystem service maps to support collaborative agroecosystem management and planning, while addressing the main caveats of pollination ES mapping: (i) lack of regional pollinator abundance knowledge; (ii) limitations of pollination ES supply and demand mapping methods; and (iii) the need for a stronger involvement of stakeholders in these assessments.

For that, we combined spatial pollination supply model outputs with detailed spatially explicit pollination demand maps to identify potential met and unmet ES demand. The analysis was supported by a participatory process with key stakeholders, that included individual interviews and workshops. Mapping limitations are explored and the suitability to communicate pollination service delivery to relevant stakeholders is discussed. In the end, lessons are drawn on how pollination ES maps can be improved in terms of their intelligibility and on how they can support collective discussions about collaborative resources management and planning.

2. Methods

2.1. Study area

This research was conducted in the Sudoeste Alentejano and Costa Vicentina Natural Park (PNSACV), located in the south-western corner of Portugal (Figure 1). This protected area is one of the few remaining well-preserved coastlines in Western Europe. It has a terrestrial and a marine component, covering 60 568 ha in land and 28 858 ha in the sea, hosting a large variety of habitats with multiple endemic flora and fauna. Agricultural land use is important, accounting for 15% of the area. The development of the Mira Irrigation Perimeter (PRM) (Figure 1) has enabled the expansion of irrigated crops and intensive farming that have been progressively replacing traditional agricultural practices, more compatible with natural resources conservation. The irrigation infrastructure was developed prior to the classification of the Park as a protected area in 1995, creating since then a conflict between food production and ecological conservation, that opposes local landowners to the Park management. The use of agrochemicals, habitat loss and the spread of invasive

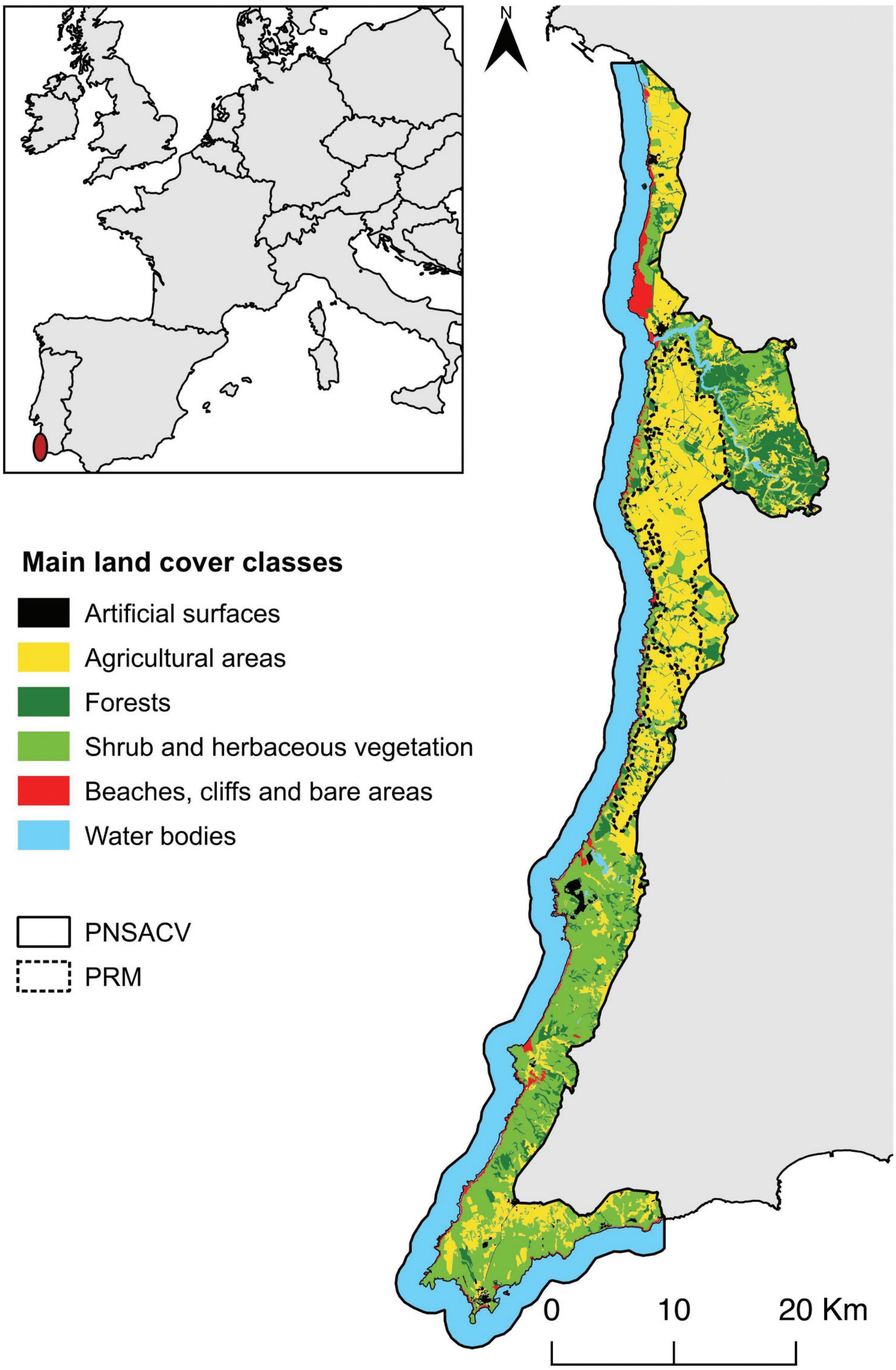

Figure 1. Study area location and main land cover classes.

species (e.g. acacia) are the main pressures to agroecosystems within the PNSACV.

The production of fruits and vegetables has been growing due to the ideal Mediterranean climate and soil conditions. For instance, exports of small fruit crops (raspberry, blackberries and blueberries) cultivated in greenhouses reached a value of 54 M€ in 2018. This growth has led to a higher demand for pollination services. Currently, local farmers rent managed honeybee hives provided by beekeepers or purchase managed bumblebees to commercial pollination service providers.

There are no data about wild pollinators and their pollination networks in the PNSACV. Nonetheless, this landscape is composed by semi-natural Mediterranean habitats known to host wild pollinators (Petanidou and Lamborn 2005; Potts et al. 2005). Although the actual contribution of wild pollinators to current yields is unknown, their presence is presumably important for the regulation of ecological processes and as an environmental insurance against potential managed pollinator declines.

2.2. Study design

The study was organized around three main stages and sought to consult and engage local stakeholders throughout the whole process (Figure 2).

The first stage was dedicated to information gathering. For that we interviewed local farmers, beekeepers, experts and the park management to gain an understanding of the general context of agroecosystem management and planning in the area and to query the relative importance of pollination services. The identification and consultation process benefited from a previous stakeholder analysis conducted in this region (Clemente et al. 2015). We also collected the best land use and land cover (LULC) maps available and requested a map detailing location of different crops to the farmers' association.

The second stage focused on the design of the mapping approach, including the development of the pollination supply and demand mapping models that are described in the following sections. This approach was built on the 'ES cascade model' (Potschin and Haines-Young 2011) to facilitate comparability with other studies, as there is a manifold of perspectives concerning the benefits provided by pollination as an ecosystem service (Liss et al. 2013). The approach distinguishes ecosystem structures, processes, function, service supply and demand in order to provide a clear illustration of the flows between provision and benefiting areas (Figure 3).

The final stage aimed at validating the information used improve the maps' intelligibility and assess their suitability to support management. For this purpose, the results were presented and discussed with stakeholders in two participatory workshops. Suggestions and concerns highlighted in these discussions are reflected in the maps presented in this paper. In this way, the insights from the stakeholders' workshops contributed to improve and inform the mapping approach in stage 2 in an iterative process.

2.3. Modelling pollination supply

We implemented a pollination supply model by downscaling and modifying the ESTIMAP pollination model (Zulian et al. 2013a, 2013b) with the introduction of a foraging behaviour component. The original ESTIMAP-pollination model is based on the model developed by Lonsdorf et al. (2009), which estimates pollinator abundance in a habitat patch based on (i) its suitability to provide nesting sites and (ii) the amount of floral resources available within species foraging radius from the nest site. Pollination supply is then modelled with a decay function that distributes pollinator visits on each patch based on distance from nests. This model has been widely applied in many regions (Kennedy et al. 2013) and at different scales (Zulian et al. 2013a), informed by field surveys (Ricketts and Lonsdorf 2013; Kammerer et al. 2016; Davis et al. 2017), literature review

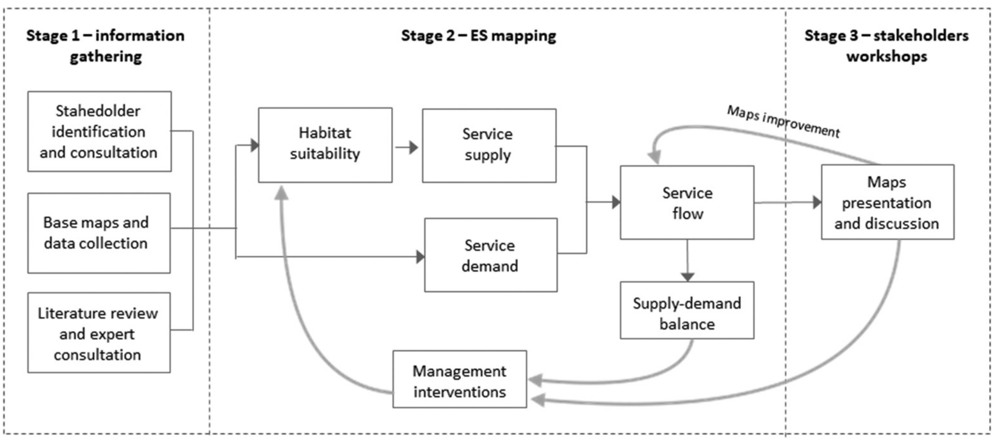

Figure 2. Study design.

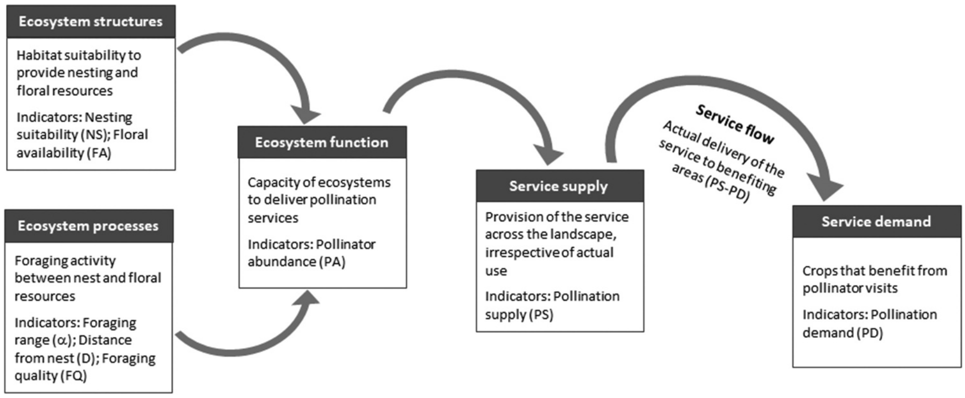

Figure 3. Cascade model for the pollination service and indicators used (modified from Potschin and Haines-Young 2011).

(Grafius et al. 2016; Verhagen et al. 2016), expert assessments (Groff et al. 2016; Koh et al. 2016) and species distribution models (Polce et al. 2013). This model is the basis of the ESTIMAP-pollination modelling framework (Zulian et al. 2013b) developed by the Joint Research Centre (JRC). Whilst originally developed to support policies at EU level, ESTIMAP provides a flexible framework where users can adapt and introduce new layers of information that are relevant to local specificities of a particular study area, as shown in Zulian et al. (2018) and Stange et al. (2017). For this reason, the ESTIMAP-pollination modelling framework was used in our study to map the pollination ES supply.

However, a main limitation of the Lonsdorf et al. model is the lack of a behaviour mechanism describing pollinators foraging activity. It is assumed that the visitation probability of a floral patch decreases with distance from nesting habitats regardless of its quality in rewarding floral resources to foragers (Olsson et al. 2015), i.e., that pollinators diffuse in all directions with equal probability. However, pollinators are central place foragers and evidence shows that they have a learning capacity in distinguishing rewarding and non-rewarding floral patches, which has an impact on the selection of the nesting site (Collett et al. 2013). This leads to an optimization behaviour in the choice of flight routes to efficiently collect floral resources (Lihoreau et al. 2010, 2012). Furthermore, it has been demonstrated that pollinator species make a trade-off between proximity and patch quality (Lihoreau et al. 2011). Thus, it is not certain that areas near habitats will benefit from a higher pollination supply, as compared with more distant ones, if the later provide more rewarding resources. To overcome this limitation, we have tested the introduction of a foraging behaviour component in the ESTIMAP-pollination service supply model, as described below.

2.3.1. Data collection and processing

The ESTIMAP-pollination model (Zulian et al. 2013a, 2013b) requires a land use and land cover (LULC) map and a look-up table that links each LULC type with its capacity to host suitable nesting sites and floral resources. The LULC of Continental Portugal for 2007 (COS 2007), produced by the Portuguese Geographic Institute (IGP), was selected as the main layer of information. Data for COS 2007 are based on imagery with 50 cm spatial resolution and has a minimum mapping unit of 1 ha (IGP 2010). Since COS 2007 does not discriminate different crop types, we used the cropland map provided by the farmers' association (Associação de Beneficiários do Mira, unpublished) that is based on the annual farmers' declarations regarding cultivated crops and irrigation water requirements.

To account for the effect of edges, a 50 m internal buffer was computed in each forest area to differentiate resource availability from forest cores, as forest edges and small patches have a positive impact on pollinator abundance (Kells and Goulson 2003; Svensson et al., 2000). Also, as riparian areas are known to provide rich pollinator habitats (Cole et al. 2015), we defined a 25 m buffer around rivers, riversides, lakes and ponds that cross natural habitats and agriculture areas.

Two scores (0 to 1) were assigned to each LULC class, regarding nesting suitability and floral availability (Table 1). Primary literature source for this scoring was Zulian et al. (2013a, 2013b), where each LULC is scored based on European datasets. Next, we consulted other sources (e.g. Maes et al. 2012; Kennedy et al. 2013; Koh et al. 2016), to understand differences in LULC scoring based on different geographical contexts. Petanidou and Lamborn (2005) was used to confirm nesting and foraging preferences for a Mediterranean context such as this study. All these sources were instrumental to draft an initial set of scores. These scores were further discussed with an ecologist expert in entomology with a strong knowledge of the study area and refined according to local specificities and potential species occurrence during spring and summer seasons. The expert identified wild solitary bees (based on *Osmia spp.*) and social wild bumblebees (*Bombus spp.*) guilds as surrogates for the local wild bee community. Due to data shortage concerning specific spatial occurrences, we used the same scores for both guilds. The LULC vector layer was then converted in

Table 1. Nesting suitability (NS) and floral availability (FA) scores for each LULC type.

Classes	Land Cover	NS	FA
Artificial surfaces[1]	Continuous urban fabric	0	0
	Discontinuous urban fabric and urban green spaces	0.3	0.3
Agricultural areas[1]	Non-irrigated arable land	0.2	0.2
	Permanently irrigated arable land	0.1	0
	Orchards	0.5	0.9
	Vineyards and olive groves	0.5	0.6
	Pastures	0.3	0.3
	Heterogeneous agricultural areas	0.4	0.4
	Agroforestry	1	0.6
Crop types[2]	Small fruits: raspberries, blackberries and strawberries	0.1	0.9
	Fruits	0.5	0.9
	Brassicas	0.1	0.9
	Vegetables	0.4	0.8
	Flowers	0.1	0.9
	Potatoes	0.1	0.7
	Wheat and others	0	0
Forests[1]	Cork oak	1	1
	Eucalyptus	0.6*/0.8**	0.7*/0.9**
	Pine	0.7*/0.9**	0.8*/0.9**
	Mixed broad-leaved and coniferous forests	0.7*/0.9**	0.6*/0.7**
Shrub and herbaceous vegetation associations[1]	Natural grassland	0.8	1
	Shrubs	0.9	1
	Sclerophyllous vegetation	0.9	0.8
	New plantations	0.8	0.5
Open spaces[1]	Beaches, dunes and cliffs	0.3	0.3
	Sparsely vegetated areas	0.7	0.3
Water bodies[1]	Wetlands	0.4	0.7
	Inland waters	0	0
Riparian areas[1,3]	Riparian corridors inside natural habitats	0.8	0.8
	Riparian corridors inside agricultural areas	0.5	0.5

*Core forest; **50 m edge and open forests.
Sources: [1]COS 2007; [2]PRM Crop types; [3]Hydrography

two 25 m-resolution raster maps for nesting suitability and floral availability using QGIS 2.18.

2.3.2. Pollination supply model

The methodological outline of the original and modified pollination supply model is presented in Figure 4. The capacity of each LULC class (Figure 4(a)) to support insect pollinators and deliver pollination services is derived by the nesting suitability of each cell (Figure 4(b)) and availability of floral resources (Figure 4(c)) around nest proximity.

Pollinators' capacity to collect floral resources within their foraging range declines exponentially with increasing distance from nests. The sum of all floral resources weighted by a distance decay function (Figure 4(d)) provides the overall foraging quality (Figure 4(e)) in each cell i $\left(FQ_{i\beta}\right)\epsilon[0,1]$:

$$FQ_{i\beta} = \frac{\sum_{j=0}^{J} FA_j \times e^{\frac{-Dji}{\alpha_\beta}}}{\sum_{j=0}^{J} e^{\frac{-Dji}{\alpha_\beta}}} \tag{1}$$

where FA_j is the floral availability in neighbour cell j, D_{ji} is the Euclidean distance between cell j and i and α_β is the foraging range for species β. This equation generates a normalized proportion between distance weighted floral availability summed across all J cells and the maximum amount of possible foraging within the species range. The relative pollinator abundance (Figure 4(f)) in each nest site i $\left(PA_{i\beta}\right)\epsilon[0,1]$ is thus derived by the map algebra between nesting suitability $\left(NS_{i\beta}\right)$ and $FQ_{i\beta}$:

$$PA_{i\beta} = NS_{i\beta} \times FQ_{i\beta} \tag{2}$$

In the original model, the distance decay function (Figure 4(d)) is applied a second time to calculate pollinator abundance visiting each cell as a proxy of pollination supply (Figure 4(g)) $\left(PS_{Li\beta}\right)\epsilon[0,1]$:

$$PS_{Li\beta} = \frac{\sum_{j=0}^{J} PA_j \times e^{\frac{-Dji}{\alpha_\beta}}}{\sum_{j=0}^{J} e^{\frac{-Dji}{\alpha_\beta}}} \tag{3}$$

where the normalized proportion scores each cell according to the distance weighted PA summed across all J cells visiting cell i.

While the original foraging model assumes that pollinators diffuse in all directions with equal probability without considering floral patch attributes, we modified the foraging model in Equation 3 to model visitation rates according to the distance from nests and respective floral quality (Figure 4(h,i)) $(PS_{Fi\beta})\epsilon[0,1]$:

$$PS_{Fi\beta} = \sum_{j=0}^{J} \frac{PA_j \times e^{\frac{-Dji}{\alpha_\beta}}}{\sum_{j=0}^{J} e^{\frac{-Dji}{\alpha_\beta}}} \times \frac{FA_i}{FQ_{j\beta}} \tag{4}$$

where the normalized proportion scores each cell according to the Euclidean distance between cell i and PA source cell j and the floral availability of cell i in comparison to the overall FQ available in the neighbourhood J. In both Equations 3 and 4, the summed value of all PS cells within the study area is equal to the total PA.

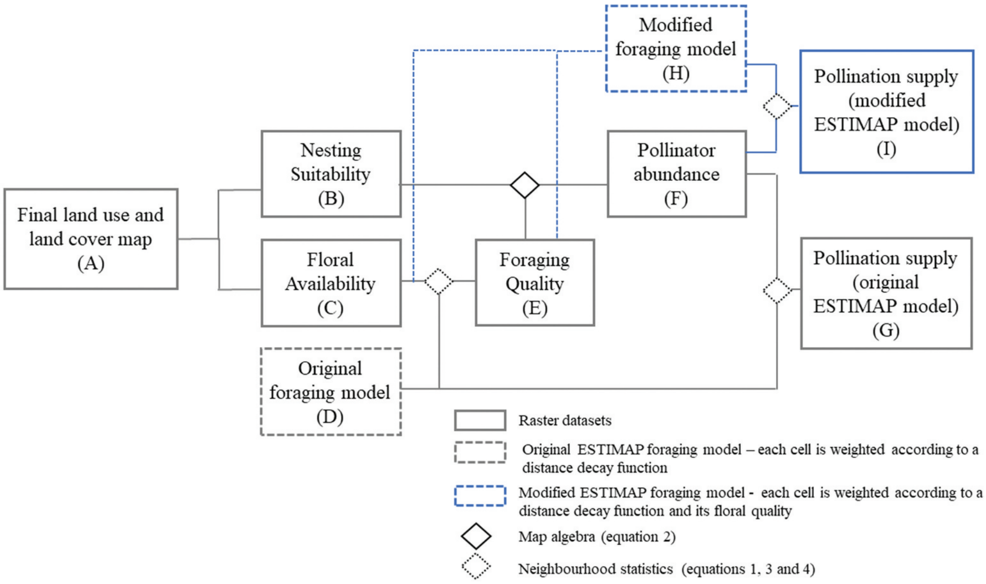

Figure 4. Original and modified ESTIMAP-pollination supply models flowchart. Blue boxes indicate ESTIMAP model modifications.

We adopted two foraging ranges based on the expert assessment: 200 m (solitary bees) and 1000 m (bumblebees). The original and modified models were applied separately to each guild in order to compare the spatial distribution of pollination supply for the two pollinator groups and to test model sensitivity to foraging range and quality. We calculated total PA and PS scores by summing both guilds assuming they are equally abundant.

2.4. Mapping pollination service demand

Demand for pollination services was mapped according to the different crop types cultivated in the Mira Irrigation Perimeter cropland map and considering the pollination dependency levels reported by Klein et al. (2007). Each dependency level has an associated range of yield loss percentage upon complete pollination deficit conditions. We used this information to assign a pollination demand (PD) level (from no demand to very high) to each crop (Table 2).

2.5. Mapping pollination flows between supply and demand areas

The demand map was used to evaluate the spatial extent of the flow of pollination supply (PS) in benefiting areas. To enable comparability with demand levels, PS was classified in qualitative classes (very low to high supply). This classification was made using quantiles, where each class covers a similar proportion of area within the PNSACV. Supply-demand budgeting was set in two balances: supply ≥ demand (satisfied demand) and demand > supply (unsatisfied demand). We chose to differentiate only these two cases, as suggested by local stakeholders, in order to simplify the reading of the obtained maps.

We simulated the effect of five hypothetical management interventions on unsatisfied demand areas (Table 3). These measures were identified based on discussions with farmers and other stakeholders during the first participatory workshop (section 2.6 below) and refer to measures generally described in the literature (c.f. Blaauw and Isaacs 2014; Dicks et al. 2015; Häussler et al. 2017). Interventions 1 and 2 aim to explore how collaborative farm management interventions could improve pollination supply values and refer to the implementation of farm hedgerows and flower strips in deficit areas (intervention 1) or in all farms (2). Interventions 3 to 5 refer to natural habitat enhancement measures (e.g. increasing floral resources) in nesting (intervention 3), foraging (intervention 4) and in both areas (intervention 5) which can lead to increased PS values, or to a sink effect of increased visitation rates in natural patches instead of dependent crops (Nicholson et al. 2019).

Table 2. Pollination demand according to dependency levels and percentages of yield loss upon the absence of pollinators in comparison to stable pollination delivery.

Pollination demand	Pollinator dependency level (% yield loss)[a]	Examples of crops
No	No increase/unknown	Wheat, potatoes
Low	Little (0–10%)	Citrus
Medium	Modest (10–40%)	Strawberries, brassicas
High	Great (40–90%)	Raspberries, almonds
Very high	Essential (90–100%)	Watermelon, zucchini

[a]Source: Klein et al. (2007)

2.6. Participatory workshops

The first participatory workshop with local stakeholders was organized with three objectives: (i) to collect stakeholders' perceptions and knowledge about pollination supply and demand; (ii) to discuss the usefulness of pollination ecosystem service supply-demand maps for communication and to support resources management and to receive their feedback regarding the approach and maps produced; (iii) to promote a debate about future perspectives for agriculture and nature conservation in the area and identify possible measures for sustainable management. We invited participants following a snowball approach, either by direct contact from the initial interviews, or by suggestion of previously contacted stakeholders.

The workshop lasted half day and was organized in two sessions. The first session consisted of a collective discussion among participants about the status and trends of pollination ES in the region. Main issues discussed included: (i) importance of the pollination ES to agriculture and ecosystem integrity; (ii) main threats to pollinators and associated impacts; (iii) status of wild and managed pollinators and (iv) pollination supply and demand trends. This discussion aimed to set a common knowledge basis before the presentation of the ES maps.

The second session was dedicated to the discussion of the pollination ES maps that had been previously produced. After a brief explanation of the model, the participants were invited to analyse and discuss the pollination supply, demand and flow maps. The following issues were addressed: (i) accuracy of the maps according to their perceptions and knowledge of the area; (ii) map intelligibility and how it can be improved; (iii) insights about possible strategies for collaborative resources management and conservation planning. At the end of the workshop an individual questionnaire was distributed to participants with the purpose of capturing their views about the usefulness of the workshop and the utility of the maps to their activities.

Further insights about the applications and limitations of the pollination ES maps were collected in a second workshop held at the same premises. This workshop did not focus exclusively on pollination ES but had a more general objective of discussing challenges in integrating ES mapping in decision-making. Thus, a wider group of stakeholders with diverse interests and influence in the Natural Park were invited, alongside the first workshop participants. The pollination mapping approach was described, together with presentations about other ES, explaining the objective, methodological procedure and main results obtained. In the end, participants were divided into two groups and asked to discuss the application of the ES maps to support land-use planning and resource management processes.

3. Results and discussion

3.1. Pollination supply

The resulting total pollinator abundance (PA) and pollination supply (PS) maps, shown in Figure 5, provide a clear picture of the study area. Overall, pollinator abundance values (Figure 5(a)) are higher in natural habitat areas outside the irrigation perimeter due to a higher availability of nesting and floral resources. Inside the agricultural perimeter, high abundance values are limited to a set of natural corridors that connect nesting and foraging sites. Pollination Supply (PS) values follow this trend, as they are a result of the distribution of pollinator abundance within the neighbourhood of each source cell. The supply map based on the original model (PS_L) shows an omni-directional pollinator diffusion (Figure 5(b)) while the modified model (PS_F) directs visitation rates according to floral availability (Figure 5(c)).

The relative values of pollinator abundance and pollination supply obtained reflect how guilds with different foraging ranges and resource requirements distribute in the landscape. Pollinator species react to landscape composition at different scales (Steffan-Dewenter et al. 2002): habitat structure and floral availability at the local scale are determinant to solitary bees due to their limited foraging ranges (Gathmann and Tscharntke 2002), while floral availability at the landscape scale is more important to bumblebees, as they are generalist pollinators and exploit a wider array of floral resources over larger distances (Westphal et al.

Table 3. Hypothetical management interventions in farms and natural habitats (NS – nesting suitability; FA – Floral availability).

Management interventions	NS	FA
Buffer with flower strips and field margins (25 m)		
(1) in unsatisfied demand areas	1	1
(2) and in all farms within a 1000 m range	1	1
Habitat enhancement		
(forest, shrubs and herbaceous vegetation and riparian areas classes)		
(3) nesting habitat	1	–
(4) foraging habitat	–	1
(5) nesting and foraging habitat	1	1

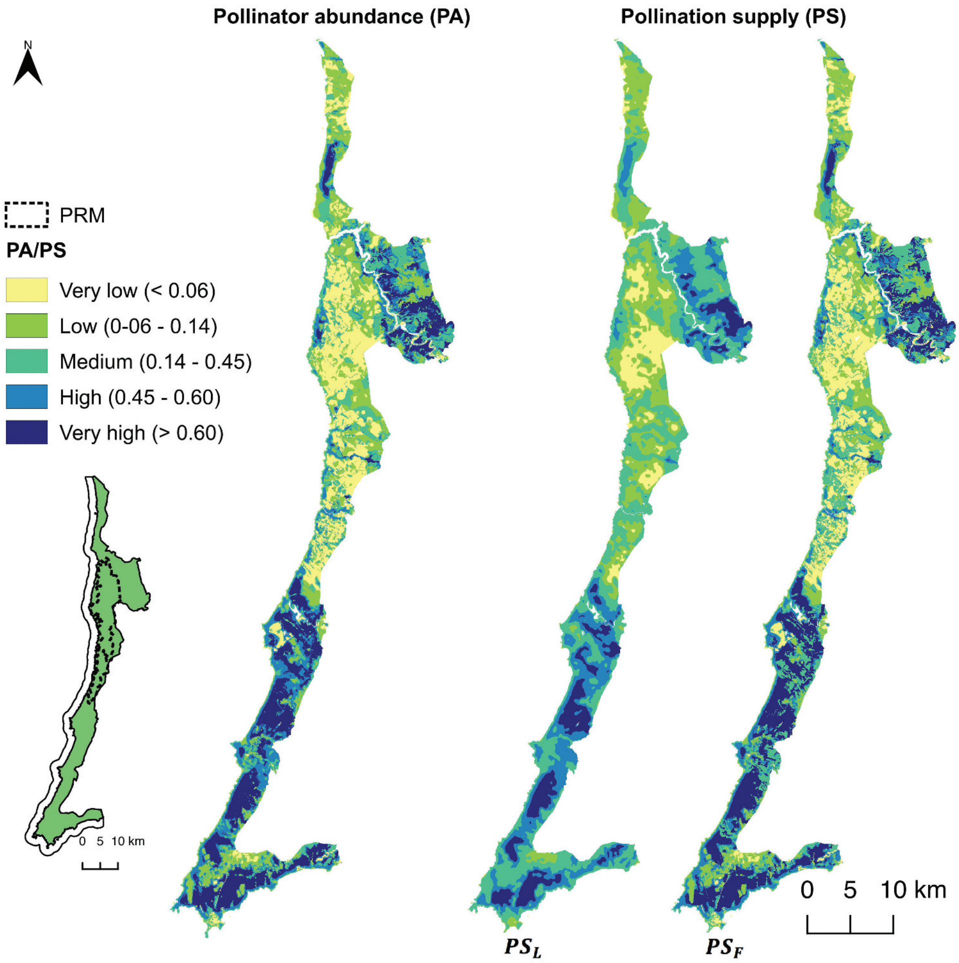

Figure 5. Total pollinator abundance (a) and original (b) and adapted (c) pollination supply model outputs.

2003). A comparison between solitary and bumblebee PA and PS maps for a selected section of the landscape (Figure 6) shows the effect of foraging in the distribution of pollination supply. There is a lower bumblebee abundance (Figure 6(d)) comparatively to solitary bees (Figure 6(a)). Solitary bees have fewer foraging opportunities due to their limited range (α = 200 m) in contrast to bumblebees (α = 1000 m), which have a larger neighbourhood matrix. However, a higher foraging range in this case covers more unsuitable floral habitats leading to a general decrease in the foraging quality (FQ) index in each nest cell, thus affecting pollination supply levels. In spite of higher abundance, solitary bees capacity to deliver high pollination supply levels is limited to the immediate vicinity (Figure 6(b,c)). On the other hand, bumblebees have the capacity to reach farther areas, resulting in a confluence to medium supply levels through the landscape due to a higher dispersion (Figure 6(e,f)).

These results also highlight the implications of a lack of behaviour mechanism component in the Lonsdorf model. In the original model, equidistant patches with different FA values are equally visited by pollinators originated on the same PA source cell (Figure 6(b,e)). The addition of a foraging selectivity component to the distance decay function in the modified model allows distributing PA according to the attractiveness of a patch in regard to the overall foraging quality near nests (Figure 6(c,f,g)).

Olsson et al. (2015) also pointed out the effects of a lack of behaviour mechanism on foraging sites selection and pollination supply modelling. They argued that the Lonsdorf model has satisfactory performances at aggregate scales and in specific local sites where landscape composition is rather homogeneous. As the landscape gets more complex, with a higher variability of resources, the model becomes less accurate in predicting pollinator visits (Olsson et al. 2015). The PS_L maps (Figure 6(b,e)) not only highlighted this issue but also exposed the model sensitivity to foraging distance increase.

Past studies chose to aggregate multiple species in a normalized final output (Lonsdorf et al. 2009; Ricketts and Lonsdorf 2013; Kammerer et al. 2016) or model only one representative guild (Zulian et al. 2013a; Koh et al. 2016; Davis et al. 2017), thus masking out this issue. Other mapping approaches also share this problem. For instance, the Lautenbach et al. (2011) and Schulp et al. (2014b) models, which serve as a basis for the pollination model of the EcoServ-GIS software (Winn et al.

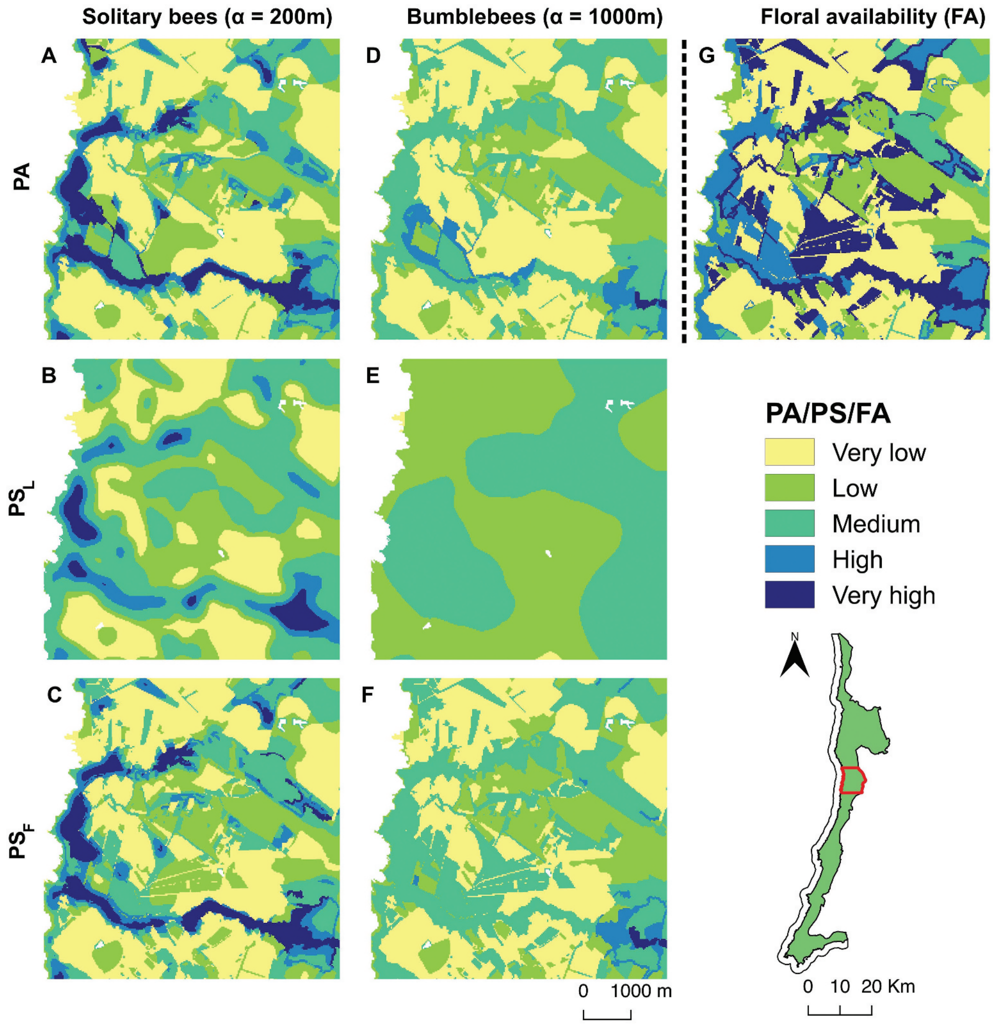

Figure 6. Pollinator abundance (PA), original (PSL) and adapted (PSF) pollination supply model outputs for solitary bees (a–c) and bumblebees (d–f) in a selected section of the landscape. PSF (c, f) is modelled according to FA (g).

2018), map visitation probability only based on the distance from pollinator habitats, regardless of their relative suitability, which can lead to higher supply values on unsuitable patches (Vorstius and Spray 2015). The lack of site selectivity during foraging constrains the validity and suitability of these models to clearly communicate pollination supply in benefiting areas, as pollinators appear to disperse in areas with no floral availability.

In this context, the PS_F (modified) maps may provide a more realistic representation of service delivery as the distance decay function varies with resource availability and pollinators are not distributed to areas with no FA. Additionally, they enable a better comparison of the potential delivery of pollination ES by solitary bees and bumblebees in terms of their foraging capacity. The comparison between PS_F maps (Figure 6(c,f)) also illustrates the dilution effect of pollinator visits across the landscape with the increase of mass-flowering areas available within species range, which is also shown empirically in European agricultural landscapes (Holzschuh et al. 2016; Kallioniemi et al. 2017). This dispersal could, however, be confined to more specific sites as species knowledge of the landscape increases over trips (Becher et al. 2016).

Field surveys about resource availability and pollinator abundance in the PNSACV would be required to validate these results. More sophisticated approaches, such as species distribution modelling based on presence/absence records and environmental predictors (e.g. slope, climate and pesticides) (Polce et al. 2013; Nogué et al. 2016), direct GIS mapping of the abundance of pollinators in each habitat area (e.g. Affek 2017) models based on central place foraging theory (Olsson et al. 2015) could provide more reliable PA and PS maps. However, the data requirements and complexity of these approaches hinder their applicability in data-poor regions such as the PNSACV.

3.2. Pollination flow between supply and demand areas

The spatial distribution of pollination ES demand obtained is presented in Figure 7. Within the Mira Irrigation Perimeter, 995 ha of cropland (35%) are dependent, at different extents, on insect pollination. Demand for pollination is high in 24% of the total cropland area, with raspberries as the most representative crop. Crop pollination is particularly critical in the south, where raspberries and other highly dependent crops are produced.

The match between the flow of pollination service supply (PS_F) with different levels of pollination demand is shown in Figure 8(a). There is a dominance of areas where demand is unsatisfied (71%). Potential-satisfied demand only occurs in areas near or within semi-natural habitats. The spatially explicit supply–demand balance allows users to target where pollination deficits are located and prioritize management actions to enhance wild pollinator services.

It should, however, be noted that the absolute meaning of the pollination supply and demand values mapped is difficult to ascertain by stakeholders and decision-makers. ES supply level classes are usually defined based on equal intervals, quantiles and on data distribution in a histogram, which means that different ranges of values will be associated to each class depending on the chosen method (Maes et al. 2012; Koh et al. 2016; Burkhard and Kruse 2017). It is difficult to associate each value to a specific supply level with no empirical pollinator abundance records and there is no possibility to transfer threshold values from other studies, as NS and FA scores only concern the respective study area. Also, demand levels transferred from Klein et al. (2007), based on a limited set of studies, do not account for local environmental conditions and farm management practices. Therefore, given the qualitative nature of the pollination supply index, the obtained supply–demand balance maps do not provide an accurate metric of mismatch, which would require extensive field validation. Nevertheless, they do provide a first regional diagnosis of potential pollination deficits. Furthermore, this approach is useful to target potential problem areas, to support a quick evaluation of possible collaborative intervention measures and for communication with stakeholders regarding intervention outcomes.

3.3. Simulation of management interventions

The spatially explicit ES supply–demand balances allow users to target where potential pollination

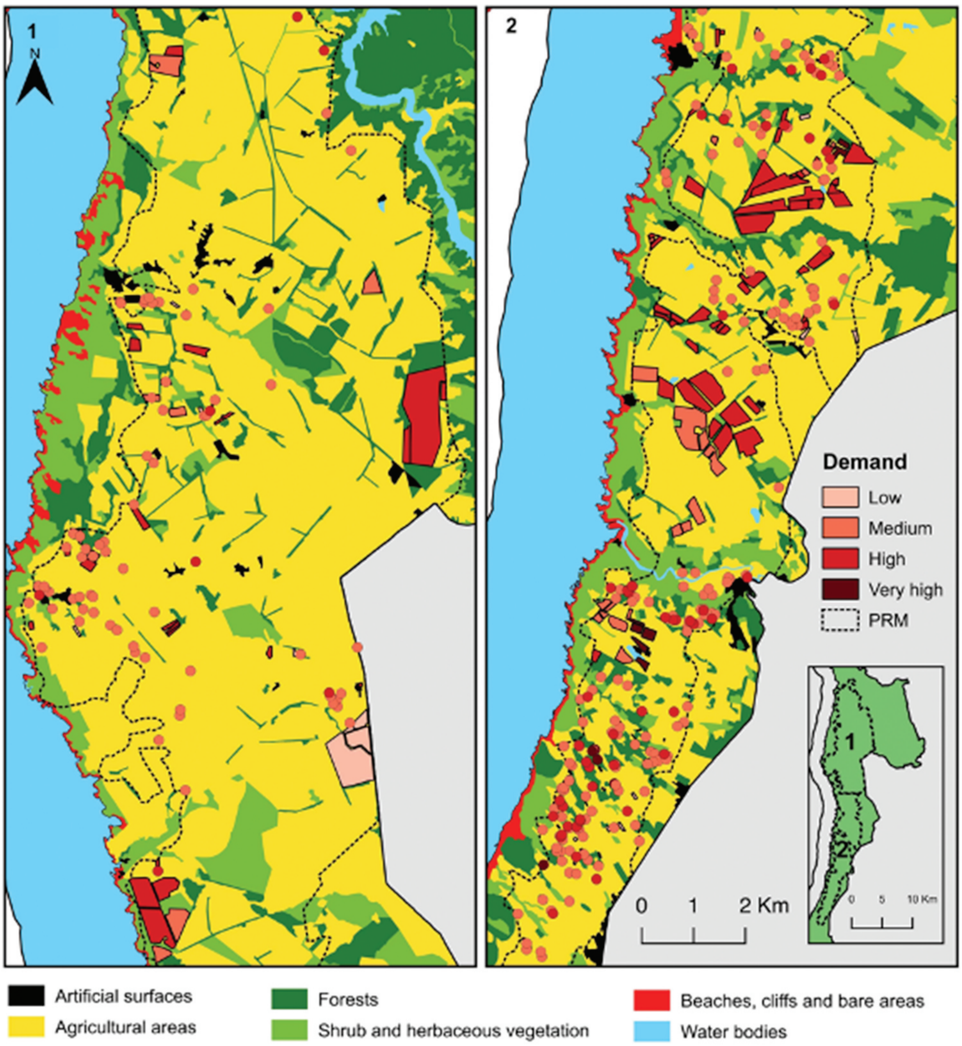

Figure 7. Crop pollination demand levels within north (1) and south (2) agricultural areas of the Mira Irrigation Perimeter (PRM).

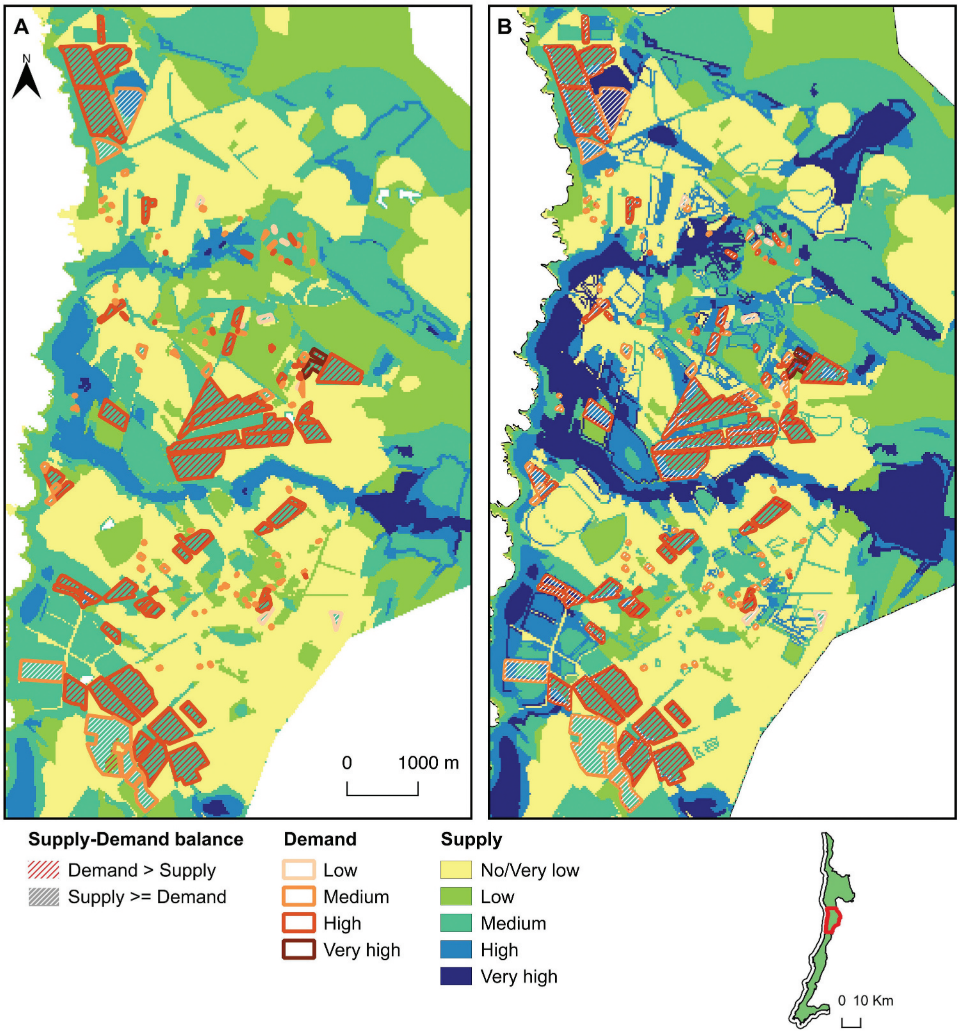

Figure 8. Match between pollination supply and demand in a selected section of the landscape (a) and after the combined introduction of management interventions 2 and 3 (b). Unsatisfied and satisfied demand levels are represented by, respectively, red and white lines.

deficits are located and prioritize management actions to enhance wild crop pollination. This practice is not yet commonly described in published literature, as spatially explicit information of where each crop type is located is rarely available. Past-published approaches relied upon aggregated and coarse data about crop share in each spatial unit to calculate a demand-weighted crop area at larger scales (Koh et al. 2016; Schulp et al. 2014a,b; Serna-Chavez et al. 2014).

Simulation of the hypothetical management interventions identified (Table 4) shows pollination supply (PS_F) values sensitivity to changes in nesting suitability (NS) and floral availability (FA) scores. Service supply increased with the introduction of a buffer with pollinator habitat in farms (Interventions 1 and 2) and nesting site enhancement (Intervention 3). The increase in FA scores in foraging habitats (Intervention 4) leads to a confluence of pollinator flows towards those areas and to a decrease in visits in cultivated areas. Enhancing both floral and nesting resources (Intervention 5) does not have an impact on pollination supply, as the resulting pollinator abundance will distribute the same relative amounts between natural and cultivated areas. The combined effect of Interventions 2 and 3, illustrated in Figure 8(b), resulted in a 20% increase in satisfied demand. However, these actions had less impact in more remote areas where PS does not meet the high demand for the service.

3.4. Stakeholders' views on mapping pollination services

3.4.1. Establishing a common understanding

The first stakeholder workshop was attended by 11 participants, including representatives of local farmers associations (2), red fruit producers (3), beekeepers (2), commercial pollination service providers (1), the natural park management services (1), environmental consultancy and local action groups (1) and the entomology expert (1).

In the initial discussion, all participants acknowledged the relevance of pollination networks for agriculture to ensure product quality. Nature conservationists

Table 4. Average total, solitary bees (*sol*) and bumblebees (*bombus*) pollination supply (PS) values in unsatisfied demand areas with the introduction of hypothetical management interventions.

Management interventions	$\overline{PS}$	$\overline{PS}_{sol}$	$\overline{PS}_{bombus}$
Baseline	0.23	0.22	0.25
Buffer with flower strips and field margins (25 m)			
(1) in unsatisfied demand areas	0.32	0.34	0.30
(2) and in all farms within a 1000 m range	0.36	0.37	0.35
Habitat enhancement			
(3) nesting habitat	0.25	0.23	0.27
(4) foraging habitat	0.16	0.20	0.11
(5) nesting and foraging habitats	0.23	0.21	0.25

highlighted the role of pollinators in sustaining ecological processes and ecosystem integrity. Beekeepers reported a perceived a decrease in abundance and diversity of wild pollinators in the Mira Irrigation Perimeter due to agricultural intensification, habitat loss, contamination with agrochemicals and resource competition with managed species. Based on their field observations, they estimate that half of the visitations to crops are done by wild pollinators. They underlined, however, that managed pollinators are essential to ensure the main crop yield production, due to the possibility of farmers manipulating honeybee abundance and visits towards areas where demand is higher. There seems to be an increase in the number of managed beehives as demand for pollination increases in the region. The recent spread of *Vespa velutina*, an invasive predator of honeybees, is seen as a threat for the maintenance of beehives, as it is viewed to potentially bring 'catastrophic' impacts to honeybee abundance. Beehive theft and associated illegal use, where health issues are neglected, are a reality in the region and brings a higher risk of disease propagation to other managed beehives. The promotion of a stronger collaboration between farmers and pollination service providers was viewed as essential to tackle these issues.

These topics triggered a discussion between nature conservationists and farmers about the role of ecological corridors in enhancing both wild and managed pollinator communities. It was also noted that these corridors could host natural enemies of pests and other ecological functions, bringing an additional incentive to their adoption. The first half of the workshop ended with a discussion between farmers associations and park management representatives about the need to adopt measures and instruments for ecosystem management. This dialogue emphasised the need of knowledge sharing between stakeholders, establishing an interesting entry point to the other half of the workshop, where maps were presented as a tool to support this communication.

3.4.2. ES maps accuracy and relevance

While analysing the distributed maps in the first workshop, participants asked some clarifications about the detail of the cartography and time period considered in the modelling exercise. One of the participants warned about recent land-use changes that have occurred. For instance, the spread of invasive species is a current problem as it disturbs native-pollinator relationships and could potentially affect pollination delivery in crops and native wildflowers. However, the available LULC datasets and the models are not able to capture this type of small-scale interactions.

Other participants emphasised the temporal mismatch between ES supply and demand, as wild pollinators activity periods do not always coincide with crop flowering seasons. Almond crops were quoted as an example by farmers, where the short flowering period desynchronized from the foraging activity of wild pollinator species dictates a total reliance on managed pollinators. In spite of the effort undertaken to adjust the mapping exercise to local conditions, there is still a need for introducing higher spatial detail and for explicitly considering variations in pollination activity during the year, to meet the needs of prospective users.

Participants considered the supply–demand balance maps that were displayed in the workshop confusing. They argued that an integration of all information in only one map would provide an easier reading and a clearer interpretation of pollination deficits, as shown in Figure 8. In spite of these limitations, participants considered the results credible, as, according to their perception, wild pollination is not able to satisfy current demand levels. Participants showed a preference for qualitative classes (very low to very high) for pollination supply maps instead of numerical classes (0–1).

It was acknowledged that the maps could be used to support the identification and enhancement of pollinator habitats in the landscape mosaic of natural areas around dependent crops to promote habitat connectivity. However, in their opinion this planning should also be supported by an economic valuation of ES in order to support the design of compensation mechanisms, such as payments for ecosystem services, as stated by a farmers' association representative.

None of the participants viewed these maps as a threat to their activities. They argued that map improvement and validation could be beneficial to agriculture and biodiversity conservation and to promote a communication channel that could lead to a more collaborative management and planning between sectors. However, beekeepers did not view these maps as useful to their needs, as particularities of beehive management were not represented. Nevertheless, they see the enhancement of wild pollination as a necessity to sustain a diverse pollinator assemblage to ensure a sustainable provision of the service.

The first workshop was positively evaluated by participants, as it was a means to promote the exchange of knowledge between different stakeholder groups, improving their awareness about the subject. One of the participants pointed out on a positive note that this type of discussion with different stakeholders, many of whom did not know each other before, is rarely promoted in the area. Some participants regretted the absence of representatives with actual decision-making power to ensure the operationalization of the conclusions, namely in the design of compensation mechanisms and other policy instruments.

3.4.3. Views on the integration of maps in natural resources management

A more diversified range of regional stakeholders (16) attended the second workshop. These included representatives from the Park management (2), farmers and agri-business (6), members of environmental NGO (2), local tourism operators (2), experts (2) and two land-use planners from the municipality of Vila do Bispo. Only two participants from the first pollination workshop were present in the second.

The second workshop provided useful information about stakeholders' perspectives on the accuracy of data used, implications for landscape planning and the power of maps to support dialogue in decision-making processes. The educational value of a spatially explicit representation of ES supply and demand was pointed out as useful to communicate the importance of ecosystem integrity to regional beneficiaries. The potential for agri-environmental measures design based on ES provision levels was identified as beneficial to agricultural landscape management and for nature conservation. According to the participants, the main challenge to this integration is to find a balanced trade-off between intensive-irrigated agriculture practices and ES provision, with acceptable costs.

Maps reflecting the pollination supply–demand balance were praised for highlighting the need to preserve habitat capacity to sustain both wild and managed pollinators. One of the participants noted the limitations of not incorporating monetary values in pollination maps, as decision-makers may not be interested in qualitative maps. As he pointed out: '*the spatial explicit information of pollination supply and demand is useful to identify unsatisfied demand. However, without the actual economic values of the indirect benefits of pollinator conservation, it is difficult to evaluate measures*'. Nonetheless, municipality planners saw the maps as useful to land-use planning processes, as a complement existing information and to identify and prioritize measures, if the information is reliable. The words legitimacy and credibility were used by these participants. Lack of technical expertise to model and map ES may be overcome by partnerships with researchers, as they view that it is more effective for them to interpret the results and to find where improvements are needed.

Finally, a representative of the farmers' association informed that since the first workshop, some of its members have discussed collectively the adoption of measures to promote sustainability of pollination ES in their fields. They have indeed started to adopt farming practices compatible with pollinator conservation and habitat enhancement and to study the design of a hedgerow network to enhance pollination and pest control services, based on native vegetation present in the Natural Park.

3.5. Practical applications

The maps demonstrated the global importance of pollination ecosystem services in the PNSACV due to a high crop demand. They served as an entry point for a workshop that aimed to test the potential of these tools as communication platforms to promote the exchange of viewpoints and knowledge between stakeholders. This workshop provided interesting insights, some of them contrasting with Hauck et al. (2013), as many of the stakeholders in the Finnish case study viewed maps a potential source of forthcoming restrictions and management constraints, which did not happen in PNSACV. This may be explained by differences in format (stakeholders workshop vs individual interviews) and the geographical context of PNSACV, where stakeholders are already used to the management restrictions imposed by being in a protected area.

There seems to be an agreement on the practical applications and limitations of pollination maps: the potential to identify suitable pollinator habitats; as a means of communication with and between stakeholders; potential to support collaborative habitat management; and the influence of space and time resolution in concealing important factors that dictate actual wild pollination. Map credibility and legitimacy are fundamental aspects in their use for landscape management and planning.

Stakeholder engagement allowed communicating the regional importance of the service to local beneficiaries and showed the importance of the continuous interaction between researchers and stakeholders. Besides, it promoted the first collective discussion of the subject in the case study area, fostering the creation of a common understanding and the exchange of experiences and viewpoints about different aspects of the pollination ES. The results highlighted the power of ES maps for communication, providing knowledge with the potential to promote a change in behaviours and practices, as the farmers' association initiative to implement pollinator-friendly measures has shown.

This work can be a starting point to the development of a more refined mapping approach with the contribution of local beneficiaries. However, future assessments should be extended to consider also the contribution of pollination in sustaining wild plant communities. As crop pollination services are mostly attributed to a strict group of species, a pollinator conservation strategy based exclusively on this ES may benefit only pollinator populations that play a role in crop pollination (Kleijn et al. 2015; Senapathi et al. 2015). In the PNSACV, pollination networks provide other indirect benefits to local residents and visitors, as wild plant communities increase landscape aesthetics and sustain processes that support other ES (Wratten et al. 2012). Thus, a pollinator conservation strategy, especially in a protected area, should target protection of both crop pollinators and those that support wildflower pollination and other indirect benefits (Kleijn et al. 2015; Senapathi et al. 2015).

The lack of an economic valuation component associated with the supply–demand balance analysis was viewed by some participants as a caveat. The calculation of the increase in crop yield due to wild pollinators and the assessment of the corresponding economic value was beyond the scope of this exercise. This issue could be further addressed with the establishment of an empirical relationship between the PS_F index and actual deposition of pollen for each crop by wild pollinators (e.g. Chaplin-Kramer et al. 2011; Ricketts and Lonsdorf 2013).

4. Conclusions

The integration of ES in decision-making and landscape planning requires the availability of information that promotes both conceptual and instrumental discussions about natural resources management (Wright et al. 2017). In this study, we show how ES supply and demand maps can be used to support an interactive discussion between stakeholders. The selection of the ESTIMAP-pollination approach, and the Lonsdorf model itself, allowed to test the suitability of the model to map pollination supply to explore the mapping of service flows between supply and demand areas in the PNSACV. The introduction of a foraging behaviour component in the original model improved the spatial representation of the service. However, there is still much room for further exploration of the proposed model modification and for testing the underlying hypothesis about foraging pollinators behaviour. The availability of field data to validate the results obtained would be fundamental to support such exercise.

This research allowed testing the potential of ES maps as communication tools with local stakeholders, contributing partially to the introduction of the ES concept in their perceptions of the PNSACV landscape. The production of a detailed crop pollination demand map and the balance between ES supply and demand were essential steps to support these dialogues, as they complement the supply maps with relevant and meaningful information for farmers and resource managers.

This research supported knowledge sharing about ES, and their dependency on natural capital, that can lead to changes in behaviours and practices, as the farmers' association initiative to implement pollinator-friendly measures has shown. In its essence, this approach highlighted the potential of ES models and maps to support debate between ES providers and beneficiaries, researchers and decision-makers, and to promote effective integration of ES in planning and management.

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