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A pan-European model of landscape potential to support natural pest control services

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ABSTRACT

Pest control by natural enemies (natural pest control) is an important regulating ecosystem service with significant implications for the sustainability of agro-ecosystems. The presence of semi-natural habitats and landscape heterogeneity are key determinants of the delivery of this service. However, to date, synthetic and consistent indicators at large scales are lacking. We developed a pan-European, spatially-explicit model to map and assess the landscape potential to sustain natural pest control. The model considers landscape composition in terms of semi-natural habitats types, abundance, spatial configuration and distance from the focal field. It combines recent high-resolution geospatial layers with empirical results from extensive field surveys measuring the specific contribution of different semi-natural habitats to support insects flying enemies providing natural pest control. The resulting maps facilitate a comparison of the relative biological control potential of different areas and show that currently a large proportion of high-productive agricultural areas in Europe has low potential. The obtained indicator can inform the formulation of policies and planning strategies aimed at increasing biodiversity and ecosystem services and can be used to assess trade-offs between different services. Potential fields of application include the Common Agricultural Policy and the EU Biodiversity Strategy, in particular the implementation of Green Infrastructure.

1. Introduction

Mapping and assessment of Ecosystem Services (ES) stands out as a major research domain that has now moved to the science-policy interface (Maes et al., 2016). The availability of spatially explicit, synthetic information is considered pivotal to mainstream the ES concept into policy-making and planning across different scales and sectors (Maes et al., 2012), and to inform decision-making on key issues such as where a mismatch between ES demand and supply is occurring or the identification of priority areas to target policies (*ibid*).

The EU Biodiversity Strategy to 2020 (EC, 2011) requires Member States to map and assess the state of ecosystems and their services in their national territory. The Strategy also requires the implementation of a Green Infrastructure, defined in a subsequent specific document as a 'strategically planned network of natural and semi-natural areas with other environmental features designed and managed to deliver a wide range of ecosystem services' (EC, 2013). The emphasis on Green Infrastructure and associated services provides an important rationale for the conceptualisation of the role of natural and semi-natural vegetation, highlighting the need for the analysis at landscape level and the distinction of different habitat typologies.

Recent advancements in ES mapping do not equally concern all ES, though. Natural pest control, also referred to as 'pest control', 'pest regulation', 'biocontrol' or 'biological (pest) control' is an important regulating service supporting crop production that has been extensively studied, but still harbours considerable knowledge gaps (Holland et al., 2017). In intensively managed agricultural landscapes, plant protection is largely based on chemical inputs, which increases production costs and environmental pollution, resulting in, among others, a negative impact on biodiversity, (agro)ecosystem functions and the provision of

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other ES (Chaplin-Kramer et al., 2011; Tschumi et al., 2015). Enhancing natural pest control has thus a high potential to contribute to ecological intensification (*sensu* Bommarco et al., 2013) and food security while reducing pressures on biodiversity and the environment. Despite the acknowledged importance of natural pest control as an ES, very few studies have attempted to develop spatially explicit models to map and assess it. In a recent systematic review, Englund et al. (2017) identified 347 cases of ES mapping, among which natural pest control turned out to be the least covered ES with only four studies.

A growing body of research has collected empirical evidence on natural pest control and its relationship with landscape structure over the last years (Chaplin-Kramer et al., 2011; Rusch et al., 2016; Holland et al., 2017). Despite the complexity of the underlying ecology, the literature points to some recurrent findings that can be generalized. Firstly, the presence of semi-natural habitats (SNH) in agroecosystems is crucial to support natural enemies by providing overwintering habitat, shelter, and alternative food; and different types of SNH have different potential to provide such resources (Holland et al., 2016 and references therein). Secondly, the capacity of local SNH to support natural enemies is dependent on landscape complexity, i.e. the amount and configuration of SNH at the landscape scale (Chaplin-Kramer et al., 2011; Jonsson et al., 2014; Rusch et al., 2016). Landscape complexity is commonly measured as the share of SNH or non-cropped habitat in a landscape sector surrounding the focal crop field within a certain radius, usually 500–1000 m (Rusch et al., 2016). Accordingly, landscape simplification proved to be correlated with increased pest abundance, (Landis et al., 2008; Meehan et al., 2011; Veres et al., 2013; Meehan and Gratton, 2015), though exceptions have been documented (see studies reported in Veres et al., 2013). Thirdly, the effect of SNH on natural pest control in the field decreases with distance (Lavandero et al., 2016; Tylianakis et al., 2006; Johnsonn et al., 2014; Holland et al., 2016). Fourthly, findings converge to support the 'intermediate landscape-complexity hypothesis' proposed by Tscharntke et al., (2012) according to which landscape-moderated effectiveness of local conservation management is highest in structurally moderate landscapes (intermediate amount of SNH), rather than in extremely simplified landscapes (due to lacking species pools) or highly complex ones (already high resource availability by existing SNH).

In this paper, we present concepts and modelling methods to build a spatially-explicit, fine-resolution, pan-European model to measure and map the potential capability of the landscape to support flying natural enemies that provide pest control services across Europe. The ES conceptual framework adopted here is the well-known ecosystem service cascade originally proposed by Haines-Young and Potschin (2010) and recently refined by Maes et al. (2016) and La Notte et al. (2017) This schematization links biodiversity and ecosystems stepwise to human wellbeing through the flow of ES (Fig. 1) and is considered particularly suitable for mapping and assessing ES (Maes et al., 2012). In this framework, 'ecosystems' are a complex network of interplaying physical structures and ecological processes, entailing flows of energy and matter through different trophic levels. A subset of the ecosystems' characteristics and properties – termed ecosystem *functions* – are potentially useful for human beings as they underpin the capacity of the ecosystem to supply the final service. This in turn generates a direct or indirect benefit to people, to which an economic value may be assigned.

The work presented in this paper aimed at: (1) developing an ecosystem service map for natural control at the European level taking into account landscape complexity and the role of SNH based on available data sources (2) determine the indications that can be derived from this map to inform policy-making and planning and (3) assessing the challenges and bottlenecks when developing such a map in order to define data that need to be collected in the future to improve it.

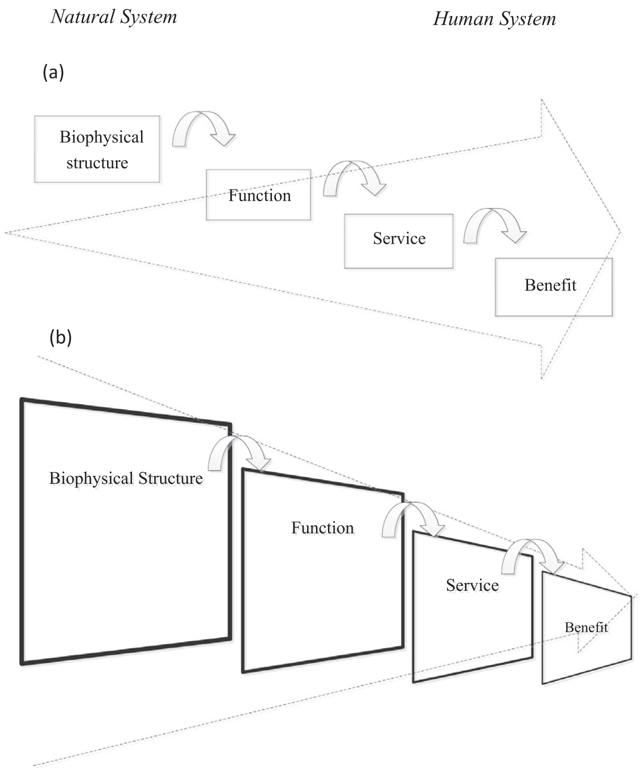

Fig. 1. (a) The traditional cascade framework with emphasis on end-use benefits; (b) re-interpretation of the cascade framework, with emphasis on the underpinning complexity of the ecological system. Source: La Notte et al. (2017).

2. Materials and methods

2.1. Model design

The model aims to quantify, in a spatially explicit way at European scale, the potential of the landscape to support insect flying predators able to control crop pests in agricultural landscapes. The abundance of these natural enemies is likely — but not necessarily — positively correlated with natural pest control services (Chaplin-Kramer et al., 2011). Therefore, the model quantifies the potential service supply for a given landscape rather than the final service delivery (reduction in pest density, higher crop yield) or related benefits, which are highly context-dependent.

Europe is schematized as a regular flat grid of square cells (resolution 100 m). The natural pest control potential in a given target cell depends on landscape complexity up to a certain distance from each cell centre. For the present study we selected 500 m as this is reported in literature as the distance at which flying natural enemies such as parasitoid species respond most strongly to landscape composition (Thies et al., 2005; Bianchi and Wäckers, 2008; Jonsson et al., 2014), but the model structure allows to set a different value. We classified SNH into four types according to the predominant vegetation type, either woody or herbaceous, and their shape, areal or linear. SNH patches extending over 25 m in all directions were defined as areal elements, whereas any element with width ≤ 25 m and length ≥ 100 m is defined as a woody linear element. Therefore, each SNH pixel was classified as either Woody Areal (WA), Woody Linear (WL), Herbaceous Areal (HA) or Herbaceous Linear (HL). Each SNH type was assigned a specific score according to its potential to support flying natural enemies, using empirical results from extensive field surveys presented in Moonen et al. (2016) (see Section 2.2). The weight of the contribution of surrounding source cells to the target cell decreases with distance between the source and the target; we used a rotationally symmetrical 2Dt-

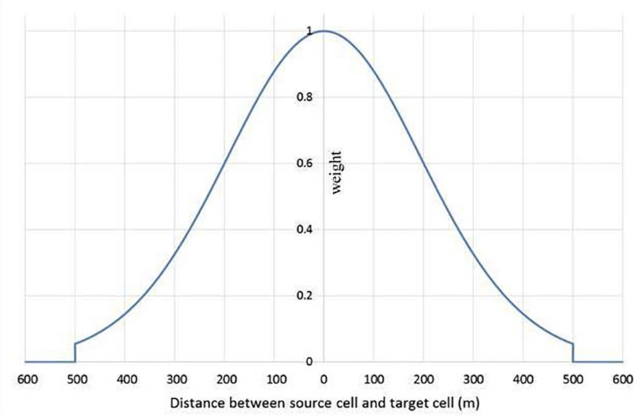

Fig. 2. Distance-weighted function used to weight the contribution of surrounding cells to the target cell.

distribution (commonly used to model insect dispersal, Robinet et al., 2012) as distance-weighted function, parameterised so to approach the shape of a normal distribution and rescaled so to assign value of 1 at distance = 0 and nullifying for distances > 500 m, as shown in Fig. 2

The model considers insects flying predators and parasitoids only, so for the sake of simplicity we neglected any barrier effect, and assumed that the function is isotropic in the two-dimensional space. A similar modelling architecture based on distance-weighted functions (also termed kernel) has been used in spatially explicit models on pollination (Lonsdorf et al., 2009; Zulian et al., 2013; Olsson et al., 2015). Each source cell is assigned a value, calculated by summing the contributions of the different SNH types occurring in it. The final potential service received by any target cell is the weighted summation of the contributions from all surrounding source cells whose centre is at distance ≤ 500 m.

Mathematically, an index in each target cell is calculated as shown by Eq. (1):

$$PCP_x = \sum_{i=1}^{n} f(r_i) \sum_{j=1}^{4} SNH_{ji} * s_j \tag{1}$$

Where:

PCP_x = Natural Pest Control Potential index in target cell x
r_i = Euclidean distance between cell i (source) and cell x (target)
$f(r_i)$ = value of the distance-weighted function at distance$r$
n = number of cells surrounding cell x for which $f(r_i) > 0$
SNH_{ji} = area share of the jth SNH type in cell i (types = Woody Areal, Woody Linear, Herbaceous areal, Herbaceous Linear)
s_j = score of the jth SNH type based on its potential to support natural enemies (flying insects)

2.2. Definition of SNH potential to support flying natural enemies

A main novelty of the proposed approach is the parameterization of the model to consider the specific contribution of different SNH types in supporting flying natural enemies (s_j scores in Eq. (1)). This is based on the results presented in Moonen et al. (2016); the applied methods are summarised here. The density of flying natural enemies was measured in 217 different SNH across 62 agricultural landscapes and four countries: Italy (Pisa Plain, N: 43°39′39.12″, E: 10°27′17.96″; 15 landscapes) Switzerland (northern part of the central plateau, N: 47°29′59.37″, E: 8°27′3.75″; 17 landscapes), Germany (upper Rhine valley, N: 49°16′27.31″, E: 8°15′58.44″; 18 landscapes) and UK (southern England, N: 51°6′55.96″, W: 1°23′39.88″; 12 landscapes). The studied agricultural landscapes were characterized by a mosaic of crops, permanent herbaceous semi-natural vegetation, as well as forest remnants, woodlots, hedgerows and tree-lines. SNH were classified into the four types described in the previous sub-section. At total of 38 HA, 61 HL, 55 WA and 63 WL SNH were sampled. To ensure that the entire range of landscape complexity characterizing the study regions was considered, landscapes were chosen along a gradient of complexity, estimated as the total coverage of SNH based on aerial photographs. This experimental design ensured that habitat type was not confounded with landscape context, and that conclusions are valid for agricultural landscapes with a wide range of complexity.

Several key groups of natural enemies were sampled in each SNH: predatory flies of the families Syrphidae (hoverflies), Asilidae (robber flies), Dolichopodidae (long-legged flies), Empididae (dance flies) predating on prey, such as aphids and other crop pests, as adults or during their larval stage and the parasitic wasps superfamilies Chalcidoidea, Braconidae and Ichneumonidae living as parasitoids on a large variety of other organisms including agricultural pests. Flying natural enemies were sampled using pan traps of three different colours mounted together (white, yellow and blue) using an experimental design described in Pfister et al. (2017) that was replicated in each of the four countries. Pan traps have been shown to be an effective sampling method for hoverflies (e.g. Power et al., 2016), as well as for flower-visiting predatory flies (Pfister et al., 2017) and parasitoids (Stephens et al., 1998).

Collected data were analysed using generalized mixed effects models with negative binomial error distribution, natural enemy abundance as response variable and SNH type (WA, WL, HA, HL) and within SNH location (edge or in the interior zone of the SNH habitat), and the interaction of the two explanatory variables, as fixed factors. An overarching analysis across countries was carried out, using SNH nested within landscape nested within country, crossed with sampling round and sampling round per country as random effects.

Moonen et al. (2016) then tested whether, within any SNH type, the predicted natural enemy abundances at the edge compared to the interior of SNH were significantly different. Results indicated that this was the case only for WA habitats. Therefore, we did not further distinguish in our mapping exercise between the interior/exterior of HL and WL SNH, whilst we discriminated between WA edges and interiors (see Section 2.3). Table 1 shows the set of scores used as parameters. We also assumed that natural enemy abundance progressively decreases when moving towards the core of WA patches: we calculated the distance of each WA-interior cell to the closest woody edge and assigned the value in Table 1 to pixels adjacent to edges. Further woody-areal interior cells were assigned a lower value, decreasing as e negative exponential function of distance and nullifying for distances > 100 m.

Statistical analyses were performed in R 3.3.1 (R Core Team, 2016) using the packages lme4 (Bates et al., 2015), effects (Fox, 2003) and lsmeans (Lenth, 2016).

Table 1
Potential natural pest control scores at the European level. Score: average abundances of flying predators predicted by the model Note: scores do not have a meaningful absolute value, but rather assess the relative potential across SNH types and within-SNH location. *maximum value for cells adjacent to edges. Source: Moonen et al. (2016).

SNH type	Score
Herbaceous Areal	26.8
Herbaceous Linear	24.7
Woody Areal – edge	45.6
Woody Areal – interior	20.7*
Woody Linear	34.4

Table 2
Corine Land Cover classification of agricultural areas.

Level 1	Level 2	Level 3
Agricultural land	Arable land	Non-irrigated arable land Permanently irrigated land Rice fields
	Permanent crops	Vineyards Fruit trees and berry plantations Olive groves
	Pastures	Pastures
	Heterogeneous agricultural areas	Annual crops associated with permanent crops Complex cultivation patterns Land principally occupied by agriculture, with significant areas of natural vegetation Agro-forestry areas

2.3. Spatial input layers

A major challenge to the development of a continental-scale, spatially explicit model on natural pest control incorporating the presence and spatial distribution of SNH in the landscape, is the availability of datasets and layers meeting two contrasting requirements: complete European coverage and fine grain resolution. To this purpose, we identified, combined and processed existing spatial datasets to produce new or improved layers fulfilling the above-mentioned requirements.

Concerning woody SNH, we used the Forest High Resolution Layer produced in the frame of Copernicus, the European Earth Observation Programme[1]. We used the tree presence/absence layer with a spatial resolution of 25 m to map the presence and spatial arrangements of woody vegetation in the agricultural landscape.

To classify woody SNH as areal and linear and to distinguish between edges or interiors in WA patches, we carried out a Morphological Spatial Pattern Analysis on the whole European High Resolution Forest layer. This is a sequence of mathematical morphological operators targeted at the description of the geometry and connectivity of the image components (Soille and Vogt, 2008). Based on geometric concepts only, this methodology can be applied at any scale on a binary map (foreground/background, in this case, woody cover/non-woody cover), to categorise the foreground into mutually exclusive classes. As a result, each 25 m pixel was classified as WL, WA-edge and WA-interior. Trees under agricultural use were masked out and excluded from the analysis, as we wanted to measure the specific contribution of SNH.

To identify the presence and spatial distribution of herbaceous SNH in agricultural areas, we elaborated on the pan-European map of semi-natural vegetation abundance in Europe produced by García-Feced et al. (2014). These authors estimated the abundance of herbaceous SNH in agricultural land based on the spectral analysis of satellite imagery in combination with geospatial data from different sources.

The final layer has a resolution of 100 m and the value of each pixel represents the share of land identified as semi-natural herbaceous vegetation. Validation tests reported by the authors show that the map is accurate but also indicate that it tends to slightly overestimate the abundance of semi-natural herbaceous vegetation in some regions. To partly correct for this, we further processed the layer by overlapping it with two Copernicus High Resolution layers, the forest layer described above and the imperviousness layer (sealed land at 25 m resolution[2]). Whenever an overlap occurred, the semi-natural herbaceous vegetation value was corrected accordingly by deleting the overlapping cells.

Currently, there is no accurate dataset that can be used to map the presence of HL SNH at European scale. These SNH are in fact generally very small and more ephemeral, and though the latest generation of satellite products may allow their identification, this highly demanding task has not been undertaken yet. A quantification of the presence of linear elements in agricultural landscapes Europe-wide, based on the 2009 Land Use/Cover Area frame Statistical Survey (LUCAS), is presented in Van der Zanden et al. (2013). However, the resolution of the resulting map is 1 km^2, too coarse for the purposes of the present work, and LUCAS survey only reports the presence of linear elements as number of intersections along a 250 m transect. No information is provided on their size, which is indeed a key input in the modelling framework adopted here. For these reasons, the option to include this dataset as model input was discarded.

2.4. Spatial statistics

To derive synthetic information on how the calculated indicator varies across different cropping systems and regions in Europe, we carried out spatial statistical analyses by overlaying the produced map with the Corine Land Cover map. The latter classifies land cover in Europe at spatial resolution of 100 m on the basis of a hierarchical taxonomy, whereby 4 main agricultural classes are identified, furtherly subdivided in 11 sub-classes (Table 2).

Given the model architecture, the average index value over a certain area is expected to be correlated to the average abundance of semi-natural vegetation in agricultural land. However, it is interesting to see if areas with similar average SNH equipment can have significantly different natural pest control potential. We examined this at the level of administrative units (NUTS3 regions) by calculating the relation between total SNH abundance and the average index value in each region.

ArcGIS 10.4.1 (ESRI, 2016) was used to perform geospatial data processing and to implement the model; the software GUIDOS (Vogt, 2016) was used to carry out the Morphological Spatial Pattern Analysis. Spatial statistics was carried out in R 3.3.1 (R Core Team 2016), using the package "Raster" (Hijmans, 2015).

3. Results

Fig. 3 shows the pan European maps of the abundance of herbaceous and woody SNH obtained as the result of the processing described in Section 2.3. The original maps have a resolution of 100 m and 25 m respectively, but to ease visualization at the continental scale the aggregate abundance at 1 km resolution is shown. In Fig. 4, a zoom on the woody SNH map is presented to show the application of the Morphological Spatial Pattern Analysis to classify woody SNH. These maps represent intermediate results of the present exercise and are the main spatial inputs of the model.

The main output of the exercise is shown in Fig. 5, displaying the calculated value of the natural Pest Control Potential index (normalized to 0–100) at 100 m spatial resolution for all Europe. The score indicates an increasing potential of the landscape to supply natural pest control (0 = minimum potential; 100 = maximum potential). Classes shown in the legend are defined by the quantiles of scores distribution.

At the European scale, the map allows the identification of the main areas where the potential to support beneficial flying predators is relatively high or low, respectively. Significantly, large proportions of the most productive arable land in Central-Northern Europe have low values: examples include the East Midlands in the UK (Fig. 6a), the Centre-Val de Loire in France (Fig. 6b) and Saxony-Anhalt and Thuringia in eastern Germany (Fig. 6c). Other highly-productive arable regions, however, show more heterogeneous patterns, as the Po Plain in Northern Italy (Fig. 6d), where the river network and associated riparian areas, as well as the presence of remnants of in-field SNH in arable land, increase natural pest control potential. A similar pattern is observable in Brittany where non-irrigated arable land is predominant, but with pastures and complex cultivation patterns interspersed in it

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[1] Information on this layer is available at: http://land.copernicus.eu/pan-european/high-resolution-layers.

[2] Available at: http://land.copernicus.eu/pan-european/high-resolution-layers/imperviousness/view.

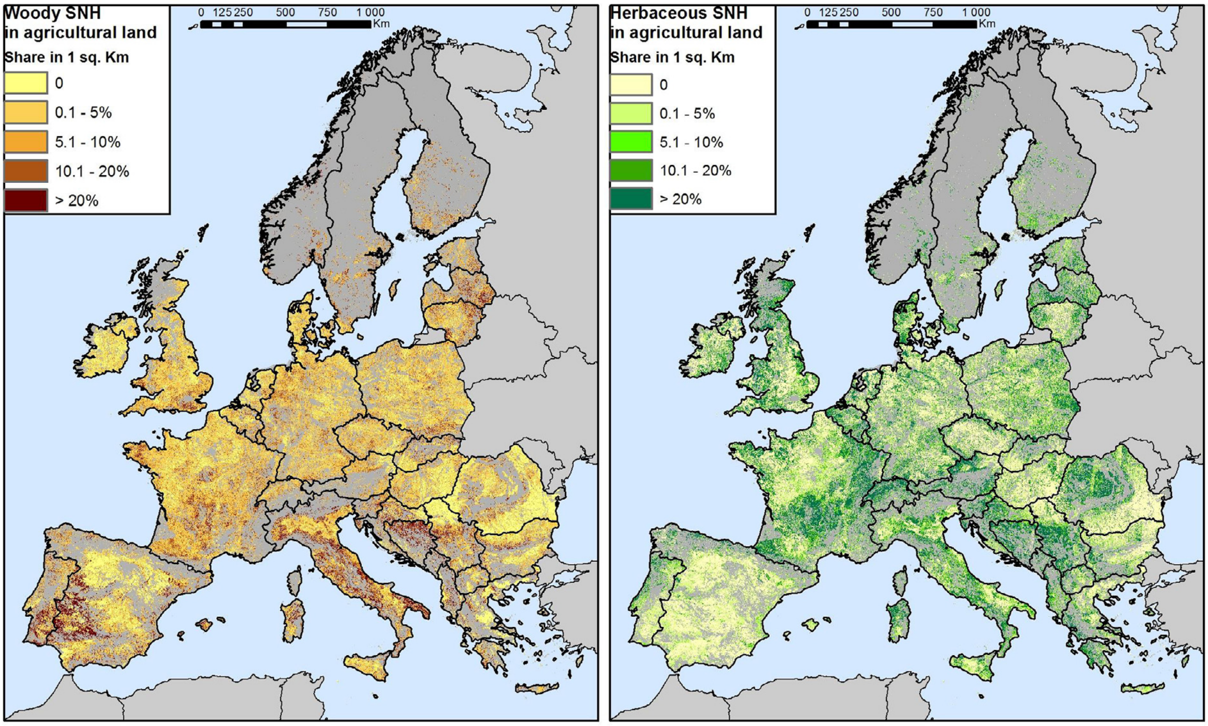

Fig. 3. Left: share of woody SNH cover in agricultural land; right: share of herbaceous SNH cover in agricultural land. Resolution: 1 km. Non-agricultural land is masked out.

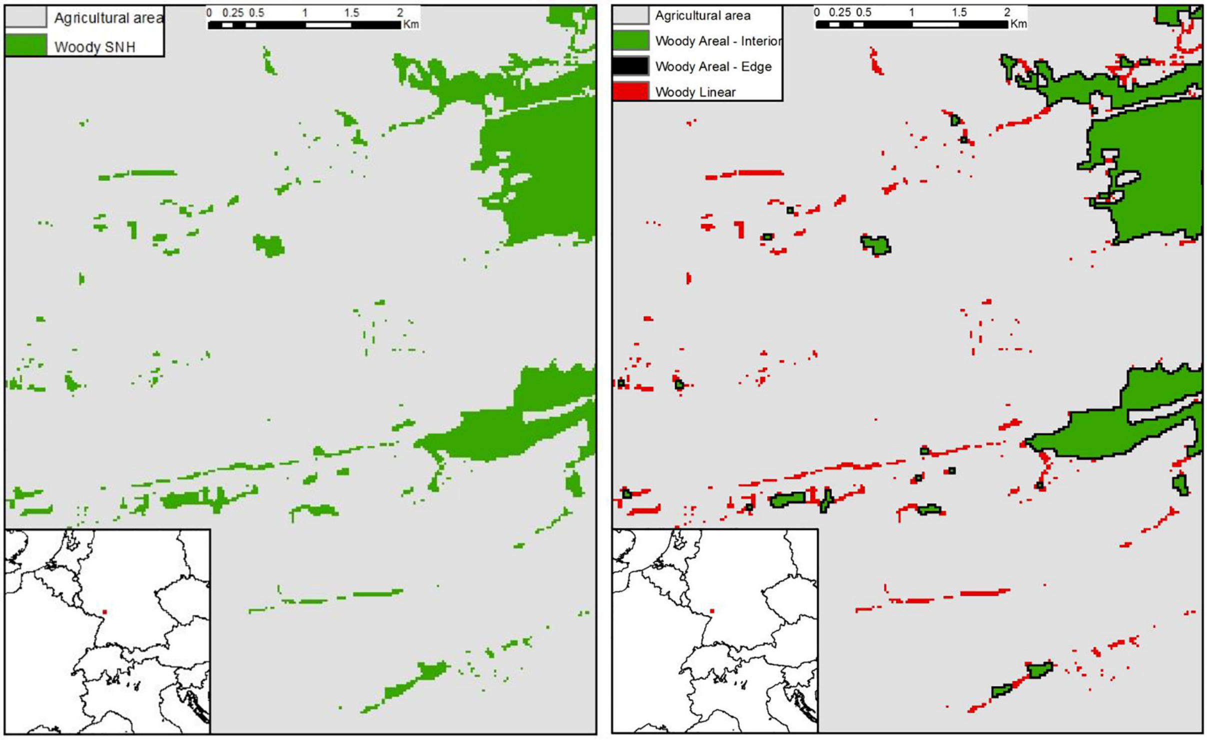

Fig. 4. Example of Morphological Spatial Pattern Analysis on the forest High Resolution Layer. Left: Original map with woody SNH in the agricultural matrix; Right: classification of Woody SNH into three mutually exclusive SNH types: WA-edge, WA-interior and Woody linear. Map resolution = 25 m.

(Fig. 6e).

Other arable-dominated landscapes standing out with very low values are the Pannonian Plain in Hungary; the Danubian plain (Fig. 7 left), which has undergone processes of land consolidation over the last years and significant decreases in semi-natural vegetation; and the arable region of Castilla y León (Central-northern Spain, Fig. 7 right).

As expected, more heterogeneous agricultural landscapes have higher index values: examples include the agroforestry systems of *dehesas* and *montados* in Spain and Portugal (Fig. 8a); the system of complex cultivation patterns and pastures in Cantabria and Galicia

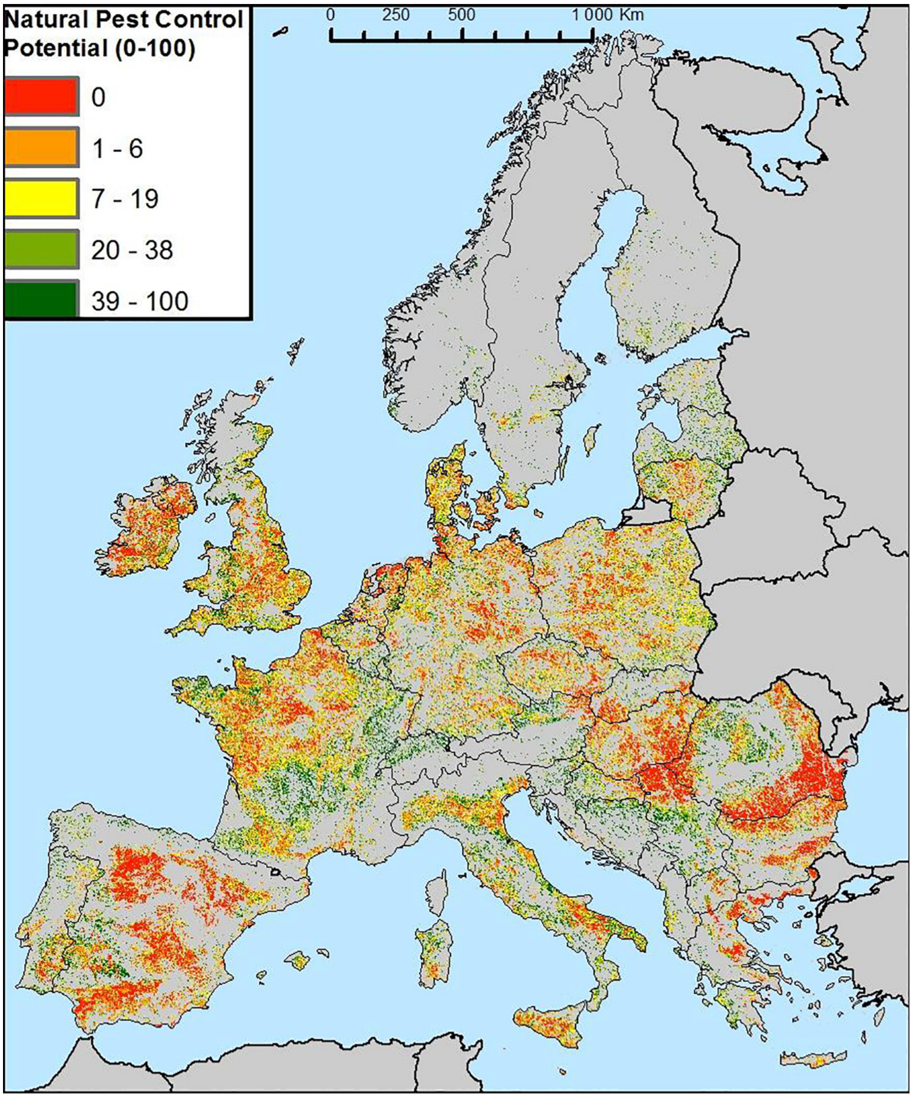

Fig. 5. Natural Pest Control Potential, dimensionless relative score index. Values are scaled to 0–100. Higher values (green cells) represent cells with higher potential to support pest control; class breaks correspond to the percentiles of the values' distribution. Spatial resolution = 100 m.

(North-Western Spain, Fig. 8b); the pastures of Massif Central in France (Fig. 8c); and the small-scaled mosaic-type arable and mixed farming agricultural landscapes of the Swiss Plateau (Fig. 8d)

Permanent crops show, on average, values similar to arable-dominated areas, although in this case the indicator may tend to be slightly underestimated in orchards and olives groves. It is not possible, in fact, with available layers, to discriminate between trees under agricultural use and woody SNH within orchards. However, non-agricultural trees inside orchards do not tend to be abundant, and the index is able to capture significant regional variations, as demonstrated by Fig. 9 showing the index values in olive plantations in Tuscany and Umbria (central Italy) and Andalusia (Southern Spain). In the first case, the more complex landscape configuration, featuring a predominance of olives but in association with complex cultivation patterns and garrigue, leads to a higher index value, compared to the more simplified landscape of intensive Andalusian olive groves.

The natural pest control potential in pasture-dominated landscapes is significantly variable: high values are found in the Massif Central (central France, Fig. 8d), Transylvania (central Romania) and along the Alpine arch. Conversely, in Western England and particularly in Ireland values are very low due to the scarcity of woody SNH.

Results from analyses described in Section 2.4 are presented in Figs. 10–12.

Fig. 10 shows the distribution of the values in the four main agricultural classes for all Europe. Arable and perennial crops have a similar distribution, with median/mean value of 6/10.9 and 5/10.3 respectively. Pastures have higher values (mean = 26.3; median = 24) and the largest variability, while heterogeneous agricultural areas have the highest scores (mean = 31.3; median = 31). Taking the distribution of the values in all agricultural land (Fig. 5), as reference we computed the share of land within each agricultural class with relative medium-high to high values (i.e. belonging to the 4th and 5th quintile of the overall distribution, value ≥ 20). Fig. 11 shows this along with the mean natural pest control value in each class. Only around 20% of arable and perennial crops area have index values ≥ 20, whilst the figures for pastures and heterogeneous areas is 54.8% and 65.4% respectively

Fig. 12 shows the average index plotted against the average abundance of SNH over NUTS3 regions. The expected correlation emerges but, interestingly, the scatterplot is quite dispersed and regions with different patterns are identifiable. To provide an example, in the diagram NUTS3 regions are highlighted in two selected member states; blue and red dots correspond to NUTS3 in Switzerland and Bulgaria respectively. Swiss landscapes have consistently higher index values whilst the opposite is observable in Bulgaria. This means that even when the total share of SNH computed at a relatively large territorial scale is similar in two areas, its configuration may determine

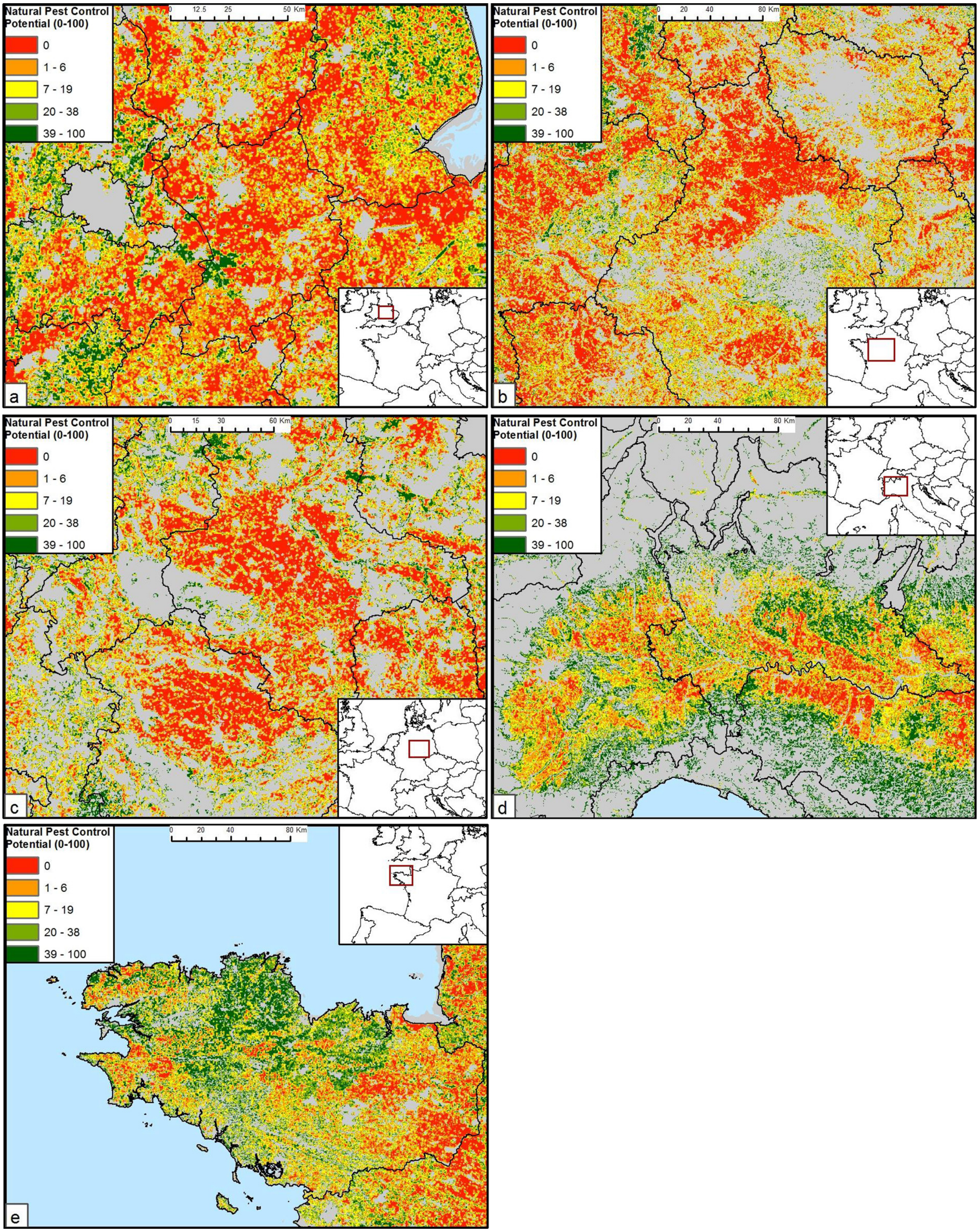

Fig. 6. Natural Pest Control Potential index in five highly productive agricultural regions with predominance of arable land: a) East Midlands (UK); b) Centre-Val de Loire (France); c) Sachsen-Anhalt and Thuringia (Germany); d) Po Plain (Italy); e) Brittany (France).

appreciable variations of the natural pest control potential.

4. Discussion

4.1. Use of the indicator for policy-making and planning

Here we provide for the first time a European map of the potential of agricultural landscapes to deliver natural pest control based on pest natural enemies (flying insects) associated with semi-natural habitats. The aim of the presented map is to convey spatially-explicit, synthetic information to inform policy making and the planning process at different scales. At a territorial scale, the model enables comparing the relative potential of different landscapes to supply natural pest control thus allowing the identification of areas with low potential, which

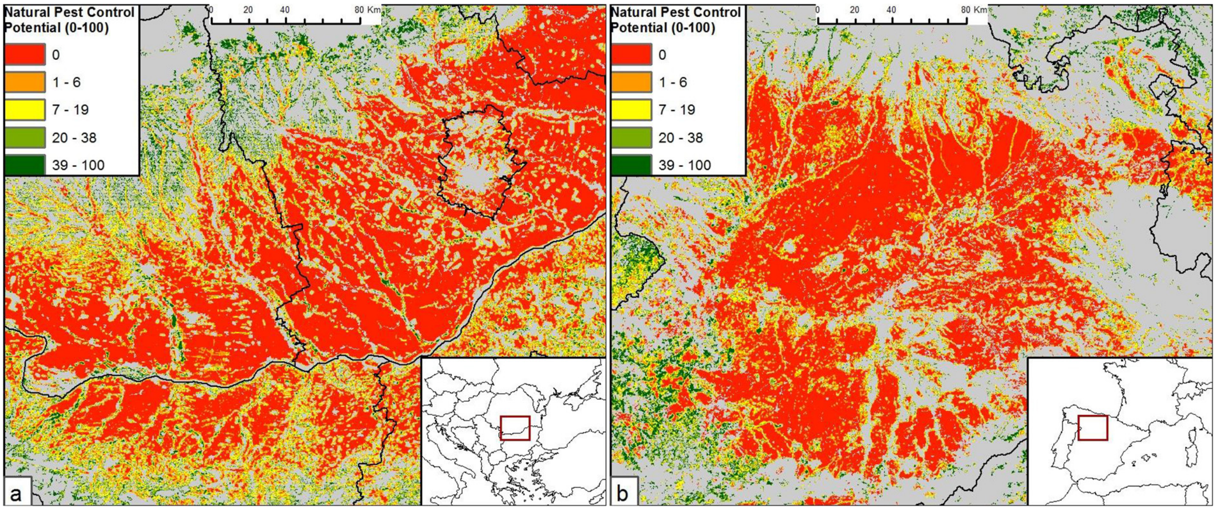

Fig. 7. a) Natural Pest Control Potential index in the Danubian Plain (Romania-Bulgaria), with dominance of non-irrigated arable land; and b) in Castilla y Leon (Spain), with irrigated and non-irrigated arable land.

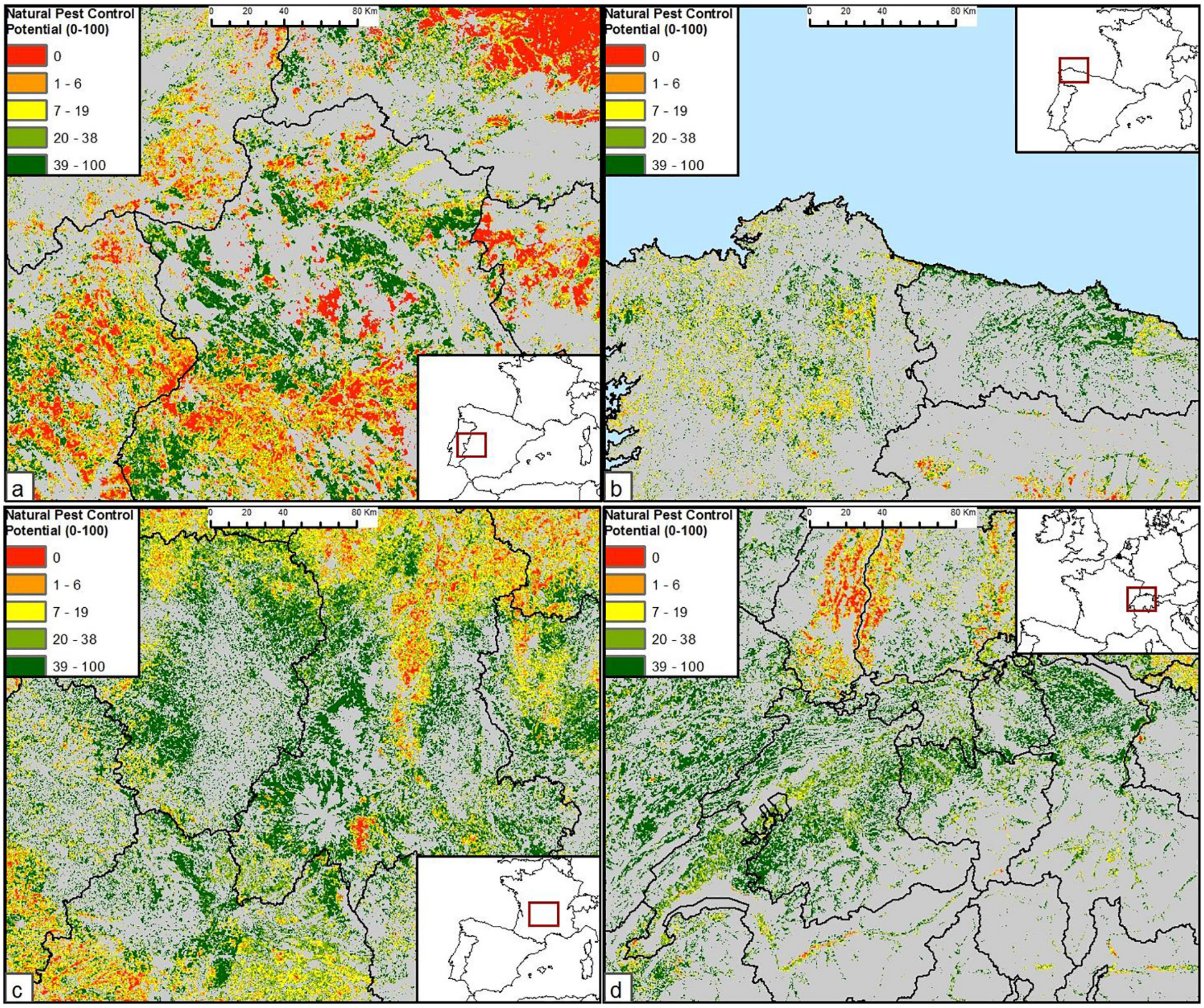

Fig. 8. Examples of regions with high Natural Pest Control Potential – a) Agroforestry systems (dehesas) in western Spain, with interspersed arable areas; b) pastures and complex cultivation patterns in Galicia and Cantabria (North-Western Spain); c) Pastures-dominated landscape in Massif Central (France) d) Small-scaled mixed-farming landscapes of the Swiss Plateau.

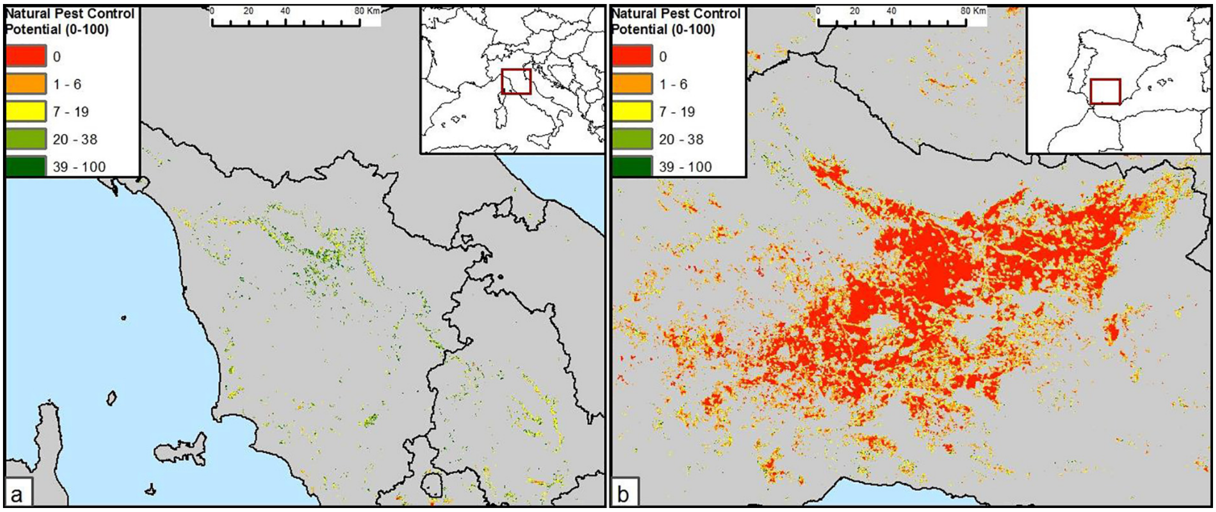

Fig. 9. Natural Pest Control Potential in olive groves in Tuscany and Umbria, central Italy (a) and in Andalusia, Southern Spain (b). Other land covers are masked out.

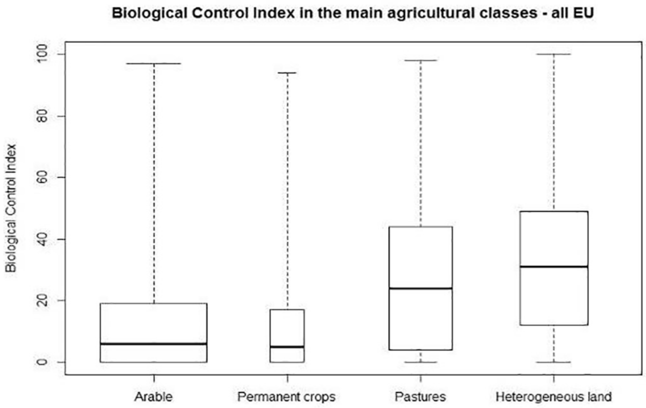

Fig. 10. Distribution of the natural Pest Control Potential index in the four main agricultural classes in Europe. The boxes define the 25%–75% quartiles; the black horizontal line represents the median; whiskers indicate the minimum and maximum values. Box width is proportional to the extent of each class.

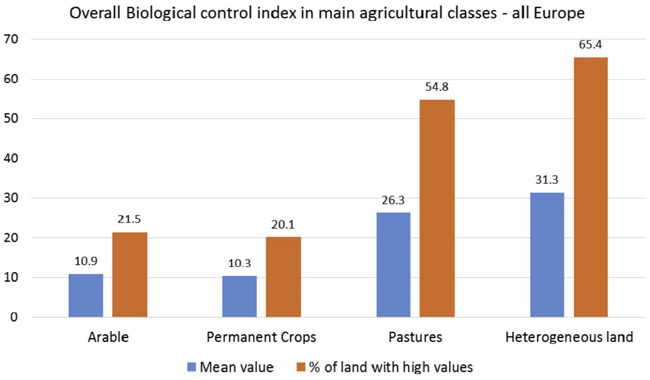

Fig. 11. Blue bar: Mean natural Pest Control Potential index in the main agricultural classes; red bar: share of land with value ≥20. Extent of the analysis: all Europe. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

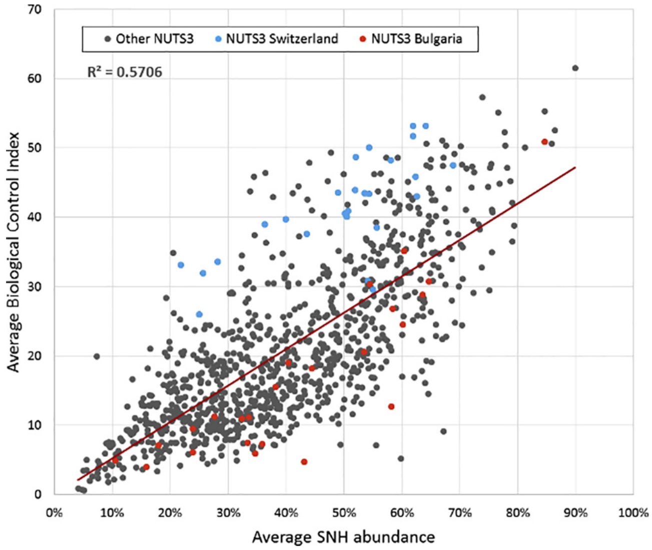

Fig. 12. Relationship between Average SNH abundance and natural Pest Control Potential in NUTS3 regions. Each point corresponds to a NUTS3 unit; blue dots are NUTS3 in Switzerland, red ones in Bulgaria. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

might be prioritized for policy interventions. Increasingly, research results are showing that the abundance of SNH in agricultural landscapes is positively correlated to the supply of ES bundles (García-Feced et al., 2014; Smith et al., 2017). Therefore, policies aimed at enhancing the presence of SNH in territories with low potential as identified by the present map would probably increase the supply of multiple ES beyond natural pest control.

More specifically, since woody edges are the most favourable habitats for insect flying predators, the enhancement of the ecological equipment in agroecosystems by increasing woody areas with a high perimeter/area ratio would be the optimal landscape design strategy to increase the potential delivery of natural pest control. Comparisons between different territorial units as the one presented in Fig. 12 would allow identifying areas with comparatively higher or lower potential, and study their specific configuration to devise management strategies. The Swiss agrarian landscape featuring small-sized fields and a heterogeneous pattern with (semi)natural grasslands and woodlots interspersed in the agricultural matrix represents a significant example. Of course, different considerations may apply if other ES or conservation goals were considered. In the case of pollination, for instance, the presence of SNH with flowering potential would be more important (Sutter et al., 2017). When aiming for biodiversity conservation, natural patches with high perimeter/area ration may not be the best option since they are usually less favourable for birds or mammals and more vulnerable to disturbance (Honnay et al., 1999; Godefroid and Koedam, 2003), or for large mammals in need of large homogenous habitat.

The proposed indicator can be used in association with other available maps to assess trade-offs and synergies between different ES. Studies featuring spatially-explicit assessments of multiple ES at European level are increasingly available (Maes et al., 2015; Mouchet et al., 2017a,b), but do not include pest control, or use indirect proxies.

The only two examples of pan-European maps linked to natural pest control are the ones proposed by Civantos et al. (2012) and Maes et al. (2017). These indicators map species richness of, respectively, terrestrial vertebrates and birds that predate on rodents, invertebrates and insects pest. Whilst they provide valuable information on potential species dynamics and distribution, both indicators can be considered to be only very indirectly linked to natural pest control in cropland as they exclude arthropods predators and do not consider landscape configuration.

The policy fields of application of the model are potentially manifold. In the frame of the EU Biodiversity Strategy to 2020, spatially explicit information can support the implementation of Green Infrastructure with the twofold objective of enhancing biodiversity and delivering a wide range of ecosystem services. Green Infrastructure is in fact an inherently spatial concept, so its effective design and management requires bringing together spatially-explicit information into a comprehensive framework including habitat conservation status, species distribution and different ES (Snäll et al., 2016). In the frame of the Common Agricultural Policy, the information can be used by Managing Authorities and other stakeholders for a more spatially-targeted implementation of Ecological Focus Areas and agri-environmental measures aiming at supporting biodiversity, a topic that has been the object of extensive research over the last years (Uthes et al., 2010; ECA, 2011; Spaziante et al., 2013).

To interpret the results in a meaningful way for decision-making, it should be emphasized again what the map does and does not represent. As explained in Section 2, natural pest control is a complex ecological process, entailing interactions and feedbacks across trophic levels. Even more than for other ES, such interactions act in a complex way and there may not always be straightforward relations between the different levels of the 'service cascade'.

As discussed in detail by Tscharntke et al. (2016), the presence of SNH *per se* does not guarantee enhanced pest control; pest outbreaks may or may not occur depending on a plethora of factors, the relationships between pest densities, crop damage and yield decrease are also context dependent, and so is the relationship between natural enemy densities and pest densities. In this case, therefore, the schematization of the ES cascade (La Notte et al., 2017) appears particularly appropriate, as it shows how the elements of the cascade are not 'equal' (Tscharntke et al., 2016, La Notte et al., 2017), having a decreasing ecological complexity when moving from functions to benefits. Drawing from the systems ecology theory, the authors propose to distinguish between three key notions when dealing with mapping and assessment of ES: biomass, interactions and information. Natural pest control is a typical case of an interaction, whereby the service derives from the multi-directional relationships between and among biotic and abiotic components. In these cases, spatial modelling is identified by the authors as fitting the purpose of ES assessment, as far as it is clear that the derived indicator does not intend to represent an actual benefit, but the potential of the landscape to provide the conditions for such service to be delivered.

Despite these considerations we confirm that the abundance of flying natural enemies is a good proxy to assess the natural pest control potential, as a positive correlation between the two variables has been reported extensively in the literature (Bianchi et al., 2006; Tschumi et al., 2015, 2016). Further empirical research is needed to study the functional relation between the values of the indicator proposed here and actual level of natural pest control measured in field. However, for aphid control, several exclusion studies demonstrated the value of specifically flying natural enemies for cereal aphid control (Schmidt et al., 2003; Holland et al., 2008, 2012). According to the intermediate landscape-complexity hypothesis (Tscharntke et al., 2012) described in Section 2, we expect this to be non-linear, but rather follow a saturation relationship. To investigate this, areas with different potentials based on the model's results can be selected to conduct empirical studies measuring the actual level of the service. Likely, other local factors will have to be taken into account as agricultural management or crop composition. A better understanding of the factors influencing the relationship between the different levels of the service cascade (landscape complexity – enemies abundance – natural pest control – effects on yield) will be fundamental to design effective measures in different landscape contexts.

4.2. Current limitations and potential developments

Compared to previous studies, the proposed modelling framework introduces two main novelties: 1) landscape structure is addressed in a more detailed way than the simplistic crop/habitat areal estimate, by considering the shape, spatial arrangement and distance of SNH in the agricultural matrix; 2) whilst current spatial models mapping landscape potential to support service-providing insects rely on expert knowledge to assess the contribution of different habitats (see e.g. models by Lonsdorf et al., 2009 or Zulian et al., 2013 on pollination), here we used empirical information based on a unique, extensive dataset derived from field surveys carried out across four European countries.

Both aspects represent advancements but also pose challenges in view of further developments. Whilst presented concepts and methods can be applied at any spatial scale, the objective of the present work was specifically to produce a map of European extent. To this regard, the first bottleneck is represented by the availability of adequate spatial datasets. The developed map is based – to the authors' knowledge – on the most recent and accurate geospatial layers representing SNH coverage in agricultural land with full European coverage (Section 2.3). These layers do not include information on other vegetation functional traits that may be important for natural enemies, though. However, one of the main results of Moonen et al. (2016) when modelling the effect of structural characteristics and floral resources on natural enemies abundance, was that the simplest model considering only SNH type, distance (interior/edge) and their interaction, proved the best one in terms of parsimony, outperforming models that included additional explanatory variables (e.g. floral display). This suggests that the main drivers of predators' abundance are some structural characteristics intrinsic to the types of SNH and the location within the element (edge/interior). Therefore, the datasets used here are considered to be able to describe the main landscape characteristics that are likely to determine the abundance of natural enemies.

The accuracy of the results will be improved once more detailed spatial layers, able to represent smaller semi-natural features occurring in the agrarian landscape better, become available, in particular as regards narrow linear herbaceous SNH and hedgerows. The new generation of very high resolution satellites images holds promise in this sense.

A second challenge is posed by the use of empirical data to feed the model. This is an improvement compared to expert-based knowledge, though field surveys to collect empirical data are time-consuming and costly, even more so if they have to cover a variety of landscapes in different locations. Given the inherently variability of the natural pest control process, replication is also needed to obtain meaningful results. This represents thus a trade-off that shall be carefully considered in view of possible refinements. One of these would be to consider geographic variability of SNH capacity to support natural enemies: in the present work it was not possible to do this and average scores from the European overarching analysis were used and considered constant in space. More samplings from a variety of different locations would be needed to extrapolate spatial variations of the scores.

The model was parameterised with data on flying insects only, therefore the contribution of ground-dwelling predators, as well as other organisms providing pest control (like birds) is not accounted for. Including information on these taxa represents another desirable future improvement. A further simplification is the assumption that natural enemies will disperse from SNH to crops, but SNH could also act as sink instead of sources and vice versa for crop areas. Finally, it was assumed that all flying insects that were collected will contribute to pest control. Owing to the number of specimens collected it was not possible to identify all individuals to species level and therefore an unknown proportion may not include pests in the diet or host range. However, we assume that the proportion of functionally inactive individuals were spread equally over the sampling units.

5. Conclusions

The developed indicator synthesizes the most advanced knowledge on the relationship between landscape complexity and natural pest control potential by insects by taking into account the type, shape and spatial configuration of semi-natural habitats in the landscape. To the authors' knowledge, this is the first wall-to-wall indicator mapping this service at the European scale, based on empirical data from extensive field surveys and on recent and fine-resolution geospatial layers of semi-natural vegetation.

The developed indicator represents the supply side of natural pest control. The next desirable step in mapping and assessing this ES would be to match it with an indicator representing the demand for this service. Arguably, not all pests associated with different types of crops are affected in the same way by the families of predators and parasitoids considered here. This would require knowing, for each crop, the main pests affecting it and the functional relation between the abundance of the predators considered in this study (of which the proposed indicator is a proxy) and that pest, as well as the relation between pest densities and decrease in crops' yield. A further refinement would be the identification of the spatial variables that are associated to pest outbreaks, which would require knowing the location of occurrence of major pest outbreaks in Europe over a certain number of years. By combining these additional pieces of information, a more comprehensive assessment of the pest control ES in Europe could be achieved. This service has the potential to maintain or increase crops yield while decreasing the use of harmful chemicals; enhancing it is therefore key in contributing to a shift towards a more sustainability of agriculture. The work presented here intends to be a step in that direction.

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