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Research Paper

Spatial alternatives for Green Infrastructure planning across the EU: An ecosystem service perspective

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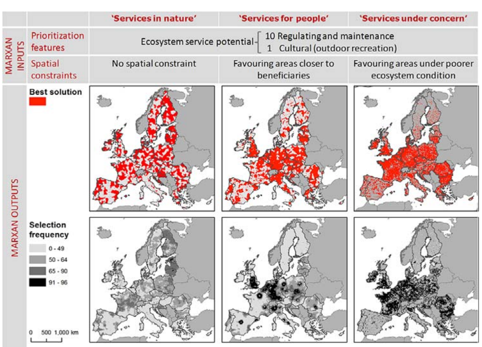
GRAPHICAL ABSTRACT



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ABSTRACT

Target 2 of the EU Biodiversity Strategy to 2020 aims at the deployment of Green Infrastructure (GI) and the restoration of at least 15% of degraded ecosystems. We assess different alternatives for the spatial planning of GI and ecosystem restoration across the European Union by using spatial conservation prioritization tools. We compared three different scenarios for the identification of priority areas in which the ecosystem service potential, beneficiaries (i.e. people) and ecosystem condition play different roles. As an example of GI restoration, we also assessed the cost-effectiveness of removal of invasive alien species in the areas prioritized under each scenario.

The comparative assessment of the spatial alternatives for GI shows synergies and conflicts. We found that GI could be efficiently established close to densely populated areas, since high multi-functionality is delivered in these locations (close to human settlements). However, restoration costs, such as the removal of invasive alien species, were higher in such areas given the influence of urban pressures. We also found that GI prioritized in areas under poor ecosystem condition would require a larger spatial extent of implementation, due to a lower ecosystem service potential per unit area.

Given the scarcity of resources for investment in GI and ecosystem restoration, win-win situations should be

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identified where GI designation can deliver several policy objectives simultaneously. The prioritization framework we have presented here could also be applied at the country or regional level to support local planning.

1. Introduction

The need for healthy ecosystems is becoming widely recognised, not just to halt the loss of biodiversity, but also to benefit from the many valuable services they provide to humans. An essential condition for healthy ecosystems is the maintenance of ecological integrity. Habitats throughout Europe are becoming increasingly fragmented and degraded due to an increase of pressures on the environment (Millennium Ecosystem Assessment, 2005). Given the scale of the challenge, more needs to be done at the European level for the benefit of people as well as nature. In this sense, Green Infrastructure (GI) planning is a policy tool that stands to improve human well-being through its environmental, social and economic values, based on the multi-functional use of ecosystems. GI designation is a key step towards the success of the EU 2020 Biodiversity Strategy. The Strategy's Target 2 (European Commission, 2011) requires that "*by 2020, ecosystems and their services are maintained and enhanced by establishing green infrastructure and restoring at least 15% of degraded ecosystems*". Ecosystem restoration has been shown to enhance not only biodiversity, but also ecosystem service potential (Barral, Rey Benayas, Meli, & Maceira, 2015; Benayas, Newton, Diaz, & Bullock, 2009). Therefore, setting priorities to restore and promote the designation of GI is essential at both the European Union and Member State level.

GI has been described 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" (European Commission, 2013). Different strategic plans could be adopted to identify priority areas for GI designation that would result in completely different spatial networks. At the EU level the European Environment Agency has proposed a methodology to identify multi-functional GI based on ecosystem services (ES); key habitats for target species; and connectivity (European Environment Agency, 2014; Liquete et al., 2015). In this approach, ES account for the natural contribution of ecosystems to generate services; usually termed 'ecosystem service potential' or 'capacity' (Syrbe, Schröter, Grunewald, Walz, & Burkhard, 2017). The socio-economic dimension, necessarily linked to the ecosystem service concept, is not considered in the identification of potential GI. This omission favours the prioritization of GI in areas with high ES potential, generally found in remote areas, where anthropogenic pressure is relatively low but also where beneficiaries of ES are therefore scarce. Moreover, if there is low demand for the service to generate benefit, only a small proportion of the ES potential will be effectively used. Ultimately, the actual flow of the service, which is a fraction of the ES potential, is steered by the demand for the service (Syrbe et al., 2017), and the spatial connection (e.g. proximity) between the service potential and demand (i.e. people). Therefore, in remote areas, benefits derived from nature would reach only a small proportion of the EU population, and the overall contribution of ES to human well-being would be limited.

Another example of GI prioritization at the EU level is the identification of key areas for GI designation based on the ES potential for a subset of services contributing to the mitigation of weather and climate change-related natural hazards, such as flood protection and mass stabilization (European Environment Agency, 2015a). This last example of GI integrates ES demand into spatial planning, taking into account the population and infrastructure requiring protection from weather and climate change impacts. Integration of socio-economic components into the GI prioritization would reinforce the link between ecosystems and socio-economic systems, resulting in a network with added value for society by increasing the provision of benefits and value of nature. In this sense, GI would also promote societal well-being by means of ecosystem services, which is also considered a key function of such a network (DG Environment, 2012).

The dependency of human well-being upon ecosystem services is widely acknowledged (Millennium Ecosystem Assessment, 2005; TEEB, 2012). Nevertheless, socio-economic systems are also key drivers of ecosystem change, exerting pressures either through the direct exploitation of ecosystem services or through the impacts caused by human activities in general (drivers of change arrow, Fig. 1). This may negatively affect ecosystem condition, compromising the long-term functioning of ecosystems and hence the benefits society can get from them. It will result in a negative effect on several components of human well-being in the long run (Millennium Ecosystem Assessment, 2005). Areas in poor ecosystem condition (i.e. degraded ecosystems) may hinder the long-term provision of multiple ecosystem services (Benayas et al., 2009; Frélichová & Fanta, 2015). Hence, in planning a multi-functional GI network capable of maintaining biodiversity and ensuring the delivery of ecosystem services, ecosystem condition should be taken into consideration.

In this context, the designation of GI closer to key socio-economic areas (i.e. cities) or those with poor ecosystem condition would require larger restoration efforts than in more intact (or remote) areas due to greater pressures and/or impacts. Restoration measures (e.g. replanting vegetation, rewetting), constitute an important investment (Tucker et al., 2013), but bring multiple benefits from the ecosystem services perspective (de Groot et al., 2013). Cost-effectiveness of ecosystem

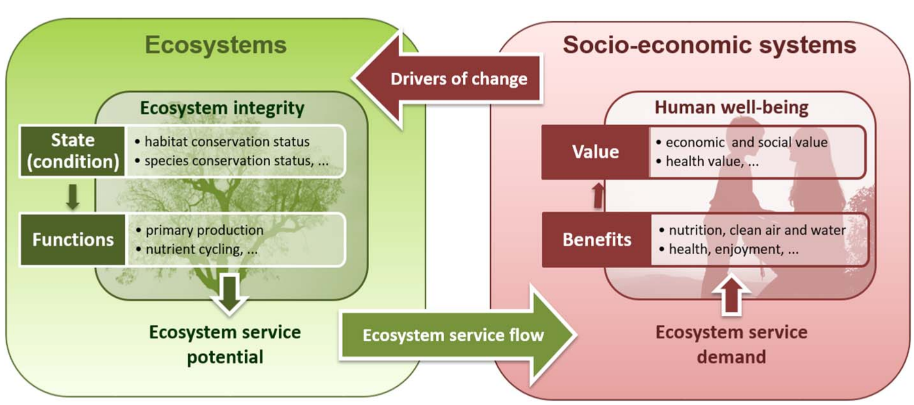

Fig. 1. Conceptual framework for EU wide ecosystem assessments linking socio-economic systems with ecosystems via ecosystem services and drivers of change, modified from Maes et al. (2013).

restoration will be spatially variable depending on the chosen location. A spatially explicit assessment of cost-effectiveness would therefore support decision-making and enable a more cost-effective allocation of economic resources to ecosystem restoration.

The main goal of this study is to assess different alternatives for the spatial planning of GI and ecosystem restoration, based on the ecosystems potential to generate services. We compared three different scenarios for the identification of priority areas in which the ecosystem service potential, proximity to service beneficiaries (i.e. people) and ecosystem condition play different roles. The ‘Services in nature’ scenario (SIN) aims to identify multi-functional areas based solely on the amount of services that ecosystems can generate (i.e. ES potential), without considering the socio-economic dimension of ES (Fig. 1). This scenario is based on the principle of GI aiming at “*protecting and enhancing nature and natural processes*” (European Commission, 2013). The ‘Services for people’ scenario (S4P) aims to identify GI that would primarily consider natural processes and ecosystem services, but also enhance their contribution to human well-being, so that a higher number of people may benefit from the services ecosystems provide. Although not all ES strictly require proximity to a population to generate benefits (Costanza, 2008), the main purpose of this scenario was to reinforce the link between ecosystems and socio-economic systems in general terms (Fig. 1). The ‘Services under concern’ scenario (SUC) prioritises multi-functional areas in poor condition ecosystems. The selected areas would therefore be closely related to socio-economic systems where drivers of change might compromise the multi-functionality of GI (Benayas et al., 2009; Frélichová & Fanta, 2015) (Fig. 1, red arrow).

The GI network identified under each scenario will be characterized by habitats with different conservation statuses. Habitats with poorer conservation status are more degraded and, therefore, require larger restoration efforts to meet the 2020 Biodiversity Strategy targets (European Commission, 2011). In this context, the scenarios were also compared in terms of the restoration effort that would be needed to improve the habitat conservation status by restoration measures. We assessed the cost-effectiveness of the removal of invasive alien species as a case study to explore the consequences of different spatial priority-setting criteria for ecosystem restoration.

Given that GI is inherently a spatial concept, we apply methods of Spatial Conservation Prioritisation (SCP) to identify important areas for their ecosystem services potential (Kukkala & Moilanen, 2013). These methods have been increasingly refined and used during the last two decades (Snäll, Lehtomäki, Arponen, Elith, & Moilanen, 2016). SCP facilitates a transparent, flexible and defensible decision-making process for the identification of key areas for either conservation or restoration (Margules & Pressey, 2000). It also allows the integration of multiple objectives that shape the complexity of GI, as in the case of our study: ecosystem services, beneficiaries and ecosystem condition.

2. Methods

2.1. Study area

The analyses were performed at a continental scale covering the European Union (EU-28), and are based on the land-use map for 2010 from the EU Reference Scenario (Baranzelli et al., 2014). The Reference Scenario is fully compliant with the ‘EU Energy, Transport and GHG emission trends until 2050 – Reference Scenario 2013’ (European Commission, 2010) and has been simulated using the Land-Use based Integrated Sustainability Assessment (LUISA) modelling platform. LUISA was developed in order to provide EU-wide projected land-use maps at a detailed geographical scale (1 ha), translating policy scenarios into land-use changes (e.g. afforestation; deforestation; abandonment of agricultural areas; urbanization) for different time periods.

The dominant ecosystem types in the EU, in the 2010 Reference Scenario land-use map, are cropland with 36%, and woodland and forest with 35% of the total extent, followed by pastures (9%). Artificial areas, including urban, industry and infrastructure cover about 5%; this is, however, the land cover type with the largest relative increase during the last decades (European Environment Agency, 2006).

The EU assessment of the conservation status of protected species and habitats, based on multiple scientific criteria (European Commission, 2015), shows that only 17% of the habitats and 17% of the species of conservation concern are considered to be in favourable conservation status. During the last years, there has been an overall trend of decline in the conservation status of habitats and species (European Environment Agency, 2015b).

2.2. Selection of priority areas for GI designation

Because GI is considered in this study as a strategically planned network of natural and semi-natural areas delivering a wide range of ecosystem services (European Commission, 2013), we identified potential areas for EU-wide GI designation using methods of Spatial Conservation Prioritisation (SCP) (Margules & Pressey, 2000). We used the ecosystem service potentials as prioritization features (described in Section 2.2.1), focusing, therefore, on the functional aspect of GI rather than on specific structures or facilities such as urban parks, wetlands or forest patches. For this purpose we used the software Marxan (Ball, Possingham, & Watts, 2009), that aims to optimize the selection of priority areas through an iterative process to meet specific levels of representation of the prioritization features. We first quantified the prioritization features in 100 km^2 hexagonal planning units (PU) that covered the whole extent of the study area (with a total of 41,608 PU). Then, we set a level of representation of 50% of the total amount of each prioritization feature, which is similar to other studies applying SCP for ES (Adame, Hermoso, Perhans, Lovelock, & Herrera-Silveira, 2014; Chan, Shaw, Cameron, Underwood, & Daily, 2006). There is inherent difficulty in choosing meaningful levels of representation for ecosystem services, and usually the choice made is to some extent arbitrary (Laitila & Moilanen, 2012; Schröter, Rusch, Barton, Blumentrath, & Nordén, 2014). Since the main goal of this study was to analyse differences between scenarios, the use of the same level of representation across scenarios ensures the comparability of the outcomes. The value of 50% is an intermediate level of representation, high enough to identify areas where ecosystem services may be enhanced. Lower levels of representation would be more related with the identification of areas only for conservation (not restoration) (Schröter & Remme, 2015), and higher values would not be operative for the spatial prioritization because the selected area would be too vast (Chan, Hoshizaki, & Klinkenberg, 2011).

When optimizing the achievement of 50% for each prioritization feature, the algorithm will prioritize areas with a high number of features, therefore reducing the total area required for GI designation. In this way, multi-functional areas are identified by means of SCP.

Moreover, the spatial aggregation of the prioritized PU can be adjusted in Marxan with a boundary length modifier (BLM). Priority areas will tend to be more spatially clustered when using high BLM values. We calibrated the BLM testing six different values (0, 0.0001, 0.001, 0.005, 0.01, 0.1 and 1), and chose as the optimal BLM the value that gave an apparent spatial pattern (no random distribution) (Ardron, Possingham, and Klein, 2010): 0.005 for the SIN, 0.05 for the S4P and 0.0001 for the SUC scenario.

For the spatial selection of PU we removed those with a share of artificial area above 50% (i.e. urban, industry and related uses, and infrastructure). Planning of GI in predominantly urban areas would require a more detailed scale of analysis (Norton et al., 2015) at which ecosystem services can be assessed at finer spatial resolution integrating relevant data into the service models such as green roofs and tree presence (not only green urban areas) (European Environment Agency, 2011). As a result, 735 PU out of 41,608 (1.8%) were excluded from the spatial prioritization.

2.2.1. Prioritization features

We included 11 ecosystem services following the Common International Classifications of Ecosystem Services (CICES) (Haines-Young & Potschin, 2013) as prioritization features: soil erosion control (Maes et al., 2015), water retention (Maes et al., 2015), net ecosystem productivity (Ivits, Cherlet, Mehl, & Sommer, 2013), relative pollination potential (Zulian, Maes, & Paracchini, 2013), potential pest control (Maes et al., 2017), habitat for common birds (Vallecillo, Maes, Polce, & Lavalle, 2016), habitat for species of conservation concern, and outdoor recreation potential (Paracchini et al., 2014). All of them, except net ecosystem productivity, are estimated as the natural contribution of ecosystems to generate services: the ecosystem service potential (listed in Table 1 and mapped in Appendix A, Fig. 6). They were quantified based on the land-use map of 2010 of the EU Reference Scenario that includes 13 land use categories (Appendix B) (Baranzelli et al., 2014).

Nursery habitat for amphibians, birds and mammals of conservation concern (i.e. those listed in the Habitats Directive (Council Directive 92/43/EEC) and Birds Directive (Council Directive 2009/147/EC)) were originally produced in this work, based on land-use suitability and species richness. These analyses were limited to amphibians, birds and mammals because of the lack of data consistency among the sources (i.e. Bioscore for land use suitability, list of species of EU conservation concern and IUCN polygons for species richness) for other groups of species.

For each group of species (amphibians, birds and mammals) we estimated the suitability of each land-use type (Appendix B) by summing the suitability scores per species provided by BioScore (Louette et al., 2010) according to Eq. (1):

$$\text{LU type suitability} = \sum \text{Suitability Value per species} \tag{1}$$

where ‘Suitability Value per species’ is equal to 2 for land uses with high suitability and 1 for medium suitability.

In this way, more species with higher suitability values result in higher suitability for each land-use type (LU type suitability). Land uses with low suitability were not included in the analysis, which is similar to other studies (Overmars et al., 2014). The LU type suitability values obtained from Eq. (1) were then rescaled from 0 to 5 and assigned to the land-use map of 2010. This gives, as a result, three different land-use suitability maps, one for each group of species, which were then weighted by the richness per pixel in species of conservation concern. Maps of species richness were derived from overlaying polygons representing species’ geographic ranges (BirdLife International, 2014; IUCN, 2008) and were also rescaled from 0 to 5. The resulting maps of nursery habitat for species of conservation concern vary between 0, where the habitat is unsuitable and/or none of the species is found, and 25 for land covers with high suitability for all species, and also where the distribution range of all species spatially match (Table 1).

In this study, we did not include provisioning ecosystem services because they are mainly driven by human inputs like energy (e.g. labour, fertilisers), and they constitute important trade-offs for biodiversity and other ecosystem services (Maes, Paracchini, Zulian, Dunbar, & Alkemade, 2012; Schröter et al., 2014).

2.3. Scenario definition

In addition to the prioritization features included in the SCP, which are the same across scenarios, Marxan allows the setting of spatial constraints for the selection of priority areas (Fig. 2). In this study, different spatial constraints were used to drive the prioritization of the spatial GI network to diverse locations, corresponding with the following specific goals or strategic plans (Fig. 2):

1. ‘Services in nature’ (SIN): the goal of this scenario was to identify priority areas for GI designation based only on the biophysical indicators of ecosystem service potential, without including any spatial constraints. From a mapping perspective, ES potential has been much more rigorously explored than the actual use of the service steered by the demand (Bagstad et al., 2014; Stürck, Poortinga, & Verburg, 2014).
2. ‘Services for people’ (S4P): in addition to meeting the goal stated for the SIN scenario, areas closer to populated places (a proxy for the final beneficiaries of services) were preferentially selected. Actually, cities and their surroundings are usually recognized as the main service benefitting areas, whether in a more or less direct way (Kroll, Müller, Haase, & Fohrer, 2012). For this scenario, we included a spatial constraint calculated as the distance of the PU to beneficiaries, by applying a kernel density function to urban patches (each one represented by a point), as delineated by the 2010 Reference Scenario land-use map. Using the population density grid computed for the same 2010 Reference Scenario (Baranzelli et al., 2014), we assigned a weighting factor to each point, calculated as the product of the mean population density and area of urban use within each urban patch. In this way, we accounted for three different components characterizing populated areas: density of urban areas in the neighbourhood (i.e. point density of the kernel

Table 1
Prioritization features for the multi-functional assessment of green infrastructure prioritization.

ECOSYSTEM SERVICES			
CICES classification*		Indicators (units)	Spatial resolution**
Regulating and maintenance	Mass stabilisation and control of erosion rates	Potential soil erosion control (dimensionless between 0 and 1)	100 × 100 m
	Hydrological cycle and water flow maintenance	Potential water retention (dimensionless between 0 and 10)	100 × 100 m
	Global climate regulation by reduction of greenhouse gas concentrations	Net ecosystem productivity (normalised index between 0 and 1)	10 × 10 km
	Pollination	Relative pollination potential (dimensionless between 0 and 1)	100 × 100 m
	Pest control	Potential pest control by bird species (species richness)	10 × 10 km
	Maintaining nursery populations and habitats	Nursery habitat for farmland common birds (dimensionless ratio)	10 × 10 km
		Nursery habitat for forest common birds (dimensionless ratio)	10 × 10 km
		Nursery habitat for amphibians of conservation concern (dimensionless between 0 and 25)	100 × 100 m
		Nursery habitat for birds of conservation concern (dimensionless between 0 and 25)	100 × 100 m
		Nursery habitat for mammals of conservation concern (dimensionless between 0 and 25)	100 × 100 m
Cultural	Physical and intellectual interactions with biota, ecosystems, and landscapes	Outdoor recreation potential (dimensionless between 0 and 1)	100 × 100 m

* Common International Classification of Ecosystem Services (CICES) Version 4.3.
** Determined by data availability and model feasibility.

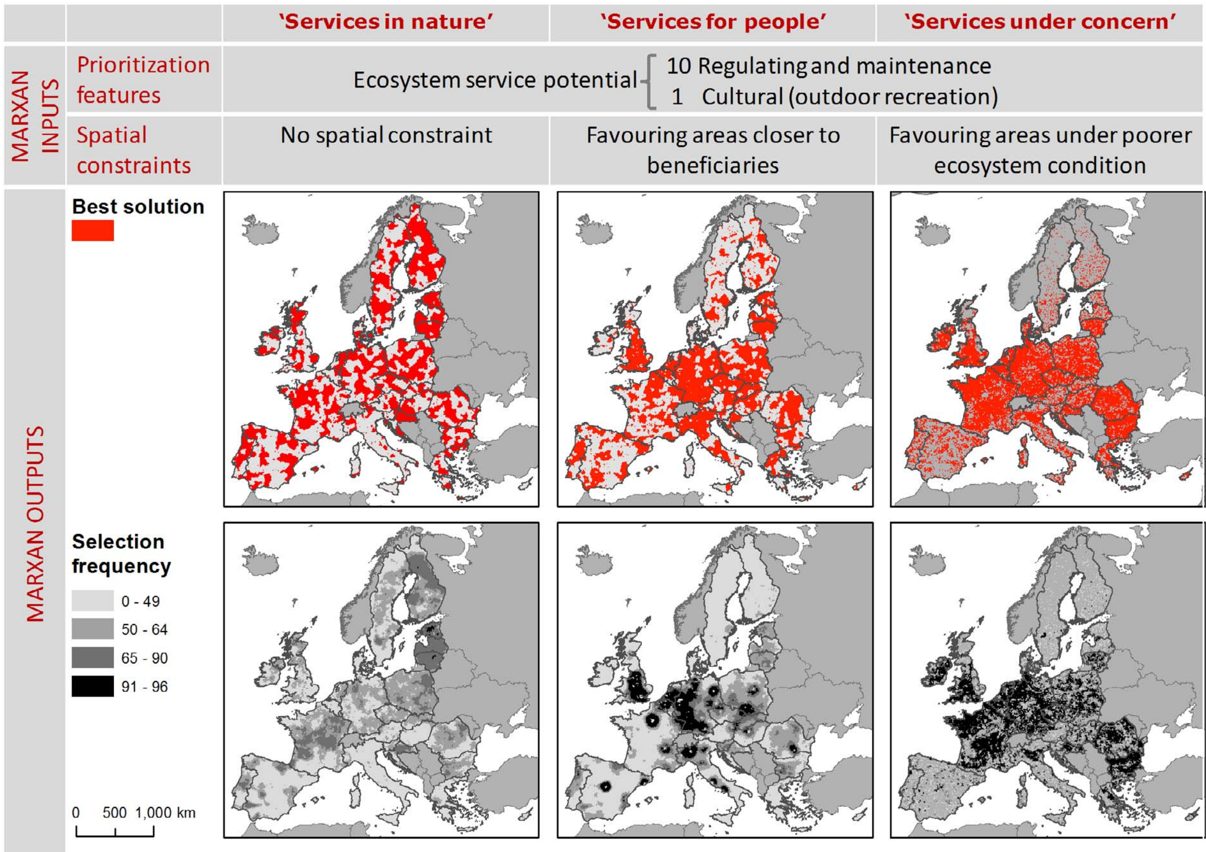

Fig. 2. Scenarios used for the GI prioritization according to their inputs (prioritization features and spatial constraints) and the outputs (best solution and selection frequency) of the spatial prioritization.

function), mean population density of each polygon with urban use, and size of the urban areas. The kernel density function was based on a 100 km radius; the distance over which is considered long distance travel. Although some ES do not strictly require proximity to a population to generate a benefit (Costanza, 2008), the main purpose of this GI scenario was to reinforce the link between the ecosystem's potential to generate services and the final beneficiaries. See Section 2.3.1 for a detailed discussion on the spatial relationship between ecosystem service potential and demand.

3. 'Services under concern' (SUC): this scenario prioritises multi-functional areas, but favours the selection of areas with poor ecosystem condition. As a proxy of ecosystem condition we took the probability of habitats being in favourable conservation status, as estimated by Maes (2013). The model was built on the reported data of Article 17 of the Habitats Directive for the assessment period 2000–2006. The model identified the share of artificial land use, arable land, pastures, proportion of land covered by Natura 2000 areas, and annual average exceedance of the critical load for nitrogen as the main factors determining conservation status across all habitats for which the EU Member States submitted an assessment. Habitats with a low probability of being in favourable conservation status are considered here as areas under poor ecosystem condition and are preferentially selected for the identification of multi-functional areas.

All three scenarios identify multi-functional areas based on the same prioritization features (Table 1), but differ in the spatial constraints used to influence the final solution (Fig. 2, Appendix A, Fig. 7).

2.3.1. Spatial relationship between ecosystem service potential and demand

As mentioned before, not all ES strictly require proximity to a population to generate a benefit (Costanza, 2008). However, we present here some arguments supporting the view that proximity of ecosystem services (and GI) to people is, ultimately, always beneficial.

The most intuitive service for which proximity to people contributes to an increase in the actual flow, and therefore the benefit generated, is outdoor recreation. In this study, we only considered the recreation potential, being the proximity to people integrated in the 'Services for people' scenario. Other services such as pollination, pest control, and nursery habitats, are classified as 'local proximal', meaning the benefit depends on proximity to human beneficiaries (Costanza, 2008). In addition, nursery habitats for different groups of species are defined as "*the presence of ecological conditions (usually habitats) necessary for sustaining populations of species that people use or enjoy*" (CICES V5.1). It follows that, if people use them or enjoy them, the closer they are, the greater the benefit. Benefits generated by water retention and erosion control depend on a directional flow from upstream (ecosystem service potential) to downstream (service demand), which, was not considered directly in our study. Despite this, the reduction of runoff would become more beneficial in areas closer to people, where it would contribute not only to reducing flood risk, but also to increasing groundwater reserves. For soil erosion control, defined as "*The reduction in the loss of material … that mitigates or prevents potential damage to human use of the environment or human health and safety*" (CICES V5.1), it is also justified that proximity to people plays a key role. Lastly, global climate regulation, as assessed here by Net Ecosystem Productivity, is a service that generates a benefit at a global scale (Costanza, 2008); however, its enhancement in areas closer to people may also contribute to the achievement of policy targets at the municipal level, such as a net reduction in CO_2 emissions of 40% by 2030 (European Commission, 2008b).

2.4. Analysis of scenario outcomes

Marxan was run 100 times for each scenario using the simulated annealing algorithm (Ball et al., 2009), each time identifying a network of selected areas or PU. This provides two useful outputs for the comparison of scenarios: the 'best (near-optimal) solution' and the selection frequency. The 'best solution' shows the selected PU that best match the prioritization features from the 100 runs. The total area and average ecosystem condition for the PU selected by the 'best solution' was calculated for each scenario.

The selection frequency is the number of times that each PU was selected from the 100 runs (ranging from 0 to 100). It indicates how irreplaceable that unit was to accomplish the required level of the prioritization features. PU selected more than 90 times were considered an 'irreplaceable area'. A small total irreplaceable area is indicative of a large flexibility, i.e., a large choice of alternative solutions for the GI designation. We also characterized irreplaceable areas by quantifying the relative amount of each prioritization feature represented within those areas, revealing the most important features driving irreplaceability in the spatial prioritization. For the S4P and SUC scenarios we also identified prioritized PU (i.e. those with high selection frequency) that have been selected regardless of the spatial constraints applied (closer to populated areas and under poor ecosystem condition respectively), contributing to the identification of critical multi-functional areas at the EU level.

Finally, we analysed differences between scenarios by performing pairwise comparisons of the selection frequency of PU and conducted correlation analysis by means of the Kendall's rank correlation coefficient.

2.5. Cost-effectiveness of removal of invasive alien plants

In 2013, the Commission adopted an EU-wide strategy promoting investments in GI to restore the health of ecosystems and ensure that nature keeps on delivering its many benefits to society (European Commission, 2013). Therefore, we propose here ecosystem restoration as a measure to be implemented in the prioritized GI areas with the goal of improving ecosystem condition and guarantee the delivery of services in the long term. Restoration of terrestrial habitats to improve conservation status can take many forms and includes measures such as rewetting, extensive grazing and mowing, replanting vegetation and/or removing invasive alien species. We compared the three scenario outcomes in terms of their cost-effectiveness using the removal of invasive alien plants as an example of a restoration measure. We chose this restoration measure for the following reasons: 1. The relevance of pressure at the EU level (European Commission, 2008a); 2. The presence of invasive alien species negatively affects habitat conservation status (European Environment Agency, 2015b; Maes, 2013); 3. The availability of EU-wide data on the distribution of invasive plant species (Chytrý et al., 2009); and 4. The availability of cost estimates for the removal of invasive alien species at the EU level (Dietzel & Maes, 2015).

We used the European map of alien plant invasion to identify restoration needs within each scenario (excluding Cyprus from the analysis due to lack of data) (Chytrý et al., 2009). The map defines an increasing level of invasion from 1 to 3 based on both the habitat properties and the propagule pressure. Within each prioritized PU we quantified the level of invasion and defined a threshold above which restoration measures would need to be applied. This threshold was set when the highest level of invasion (level 3) covers more than 25% of the total extent of the PU or when the intermediate level of invasion (level 2) covered over 75% of the PU area.

We assessed the effectiveness of the removal of invasive alien plants as the improvement in the habitat conservation status assuming full implementation of the restoration measure, in this case the complete removal of invasive species. The effectiveness is therefore a dimensionless estimate. Better conservation status of habitats has been shown to lead to an enhancement of the ecosystem service potential and to support the conservation of threatened species (Egoh, Paracchini, Zulian, Schägner, & Bidoglio, 2014; Maes et al., 2012). Changes in habitat conservation status were quantified using the model developed by Maes (2013), grounded on the Article 17 data of the Habitats Directive. The model describes habitat conservation status as a function of different pressures, including the presence of invasive alien species. The 'invasive species' factor in the model took a value of 1 when records of invasive species were present in the PU (i.e. in 19,079 PU as described above) and −1 when absent, as in Maes (2013). The implementation of invasive species control was then simulated in those PU with invasive species by simply changing the value of 1 into −1 and recalculating habitat conservation status. We estimated the effectiveness of the restoration measure in each PU based on changes in the habitat conservation status obtained before and after simulating the implementation of the invasive species control and weighting by the extent and level of invasion within each PU (Eq. (2)). Higher levels of invasion will give rise to a lower probability of successful outcome following invasive species control (Higgins, Richardson, & Cowling, 2000). To consider this, we assumed the probability of a successful outcome under invasion level 3 to be 2-fold lower than the probability of success under invasion level 2:

$$\text{Effectiveness} = \frac{(\Delta \text{PrFV} * ha_{level2}) + \left(\left(\frac{\Delta \text{PrFV}}{2}\right) * ha_{level3}\right)}{ha_{level2} + ha_{level3}} \quad (2)$$

where 'Δ Pr FV' is the difference in habitat conservation status before and after simulating the implementation of invasive species control, and $ha_{level\ 2}$ *and* $ha_{level\ 3}$ are the areas under invasion levels 2 and 3, respectively.

Information on the cost of ecosystem restoration activities is very sparse and inconsistent. Here, we used the best available information on restoration measures at the EU level (Dietzel & Maes, 2015). The authors calculated the cost of removal of invasive alien plants (invasive species control from here onwards) based on an assessment of LIFE projects, estimating an average cost of 901 € per ha. Although it may differ from real costs in some countries, the average cost is useful to compare scenarios in this study.

Since established invaders lead to higher control costs (Epanchin-Niell & Hastings, 2010), we doubled the costs for invasive species control in areas under level 3, where they are likely to be more persistent. In this way, the final cost per PU was calculated according to Eq. (3):

$$\text{Cost of Invasive species control} = (901 \times \text{ha}_{\text{level2}}) + (901 \times 2 \times \text{ha}_{\text{level3}}) \quad (3)$$

Finally, the cost-effectiveness of invasive species control was estimated for each scenario to assess where restoration investments would be more profitable. We summed the costs and the effectiveness of applying the restoration measure for the PU of the 'best solution' given by each scenario in the Marxan analysis. Total cost (Eq. (3)) and effectiveness for the 'best solution' (Eq. (2)) were expressed in relative terms to the number of hectares to be restored for each scenario. We calculated two different indicators of cost-effectiveness: effectiveness-cost ratio (the higher the ratio the more cost-effective is the scenario) and the per capita effectiveness-cost ratio. This last indicator addresses the effectiveness in relative terms accounting for population living in the PU identified by the 'best solution' that would benefit from the improvement in habitat conservation status.

3. Results

3.1. Comparison of scenarios for spatial planning of GI

3.1.1. Best solution and selection frequency

The three scenarios delivered different outcomes in terms of the best

Table 2
GI solutions under three different scenarios.

		'Services in nature' (SIN)	'Services for people' (S4P)	'Services under concern' (SUC)
Area best solution (thousands km^2)		2059	2072	2287
Ecosystem condition*		0.19	0.16	0.09
Irreplaceable area** (thousands km^2)		8	385	1154
Level of representation of the prioritization features in relative terms***	Potential soil erosion control	8%	**10%**	9%
	Potential water retention	10%	**10%**	10%
	Net ecosystem productivity	9%	**10%**	10%
	Relative pollination potential	7%	6%	7%
	Potential pest control	11%	9%	10%
	Habitat for farmland common birds	11%	9%	10%
	Habitat for forest common birds	9%	**10%**	8%
	Habitat for amphibians of conserv. concern	5%	**10%**	**11%**
	Habitat for birds of of conserv. concern	**13%**	8%	9%
	Habitat for mammals of of conserv. concern	9%	7%	7%
	Outdoor recreation potential	8%	9%	9%

* Calculated as the average probability of habitats of being under favourable conservation status for the best solution. The Dunn-test showed significant differences among scenarios for 1000 subsamplings of 5% of the data (p-values: SIN – S4P < 0.01; SIN – SUC < 0.001; S4P – SUC < 0.001).

** Planning units selected in more than 90 out of the 100 runs for the spatial prioritization with MARXAN. They were characterized by the level of representation of the prioritization features (ecosystem services) in relative terms (in bold the largest percentages for each scenario).

*** Complete names of ecosystem services are provided in Table 1.

solution and the selection frequency of the PU to achieve 50% of the total amount of each prioritization feature (Fig. 2).

While the best solutions of the SIN and S4P scenarios require almost the same amount of GI to guarantee an equivalent level of multi-functionality (50% of the total amount of the prioritization features), the SUC scenario would need an area that is about 10% larger to reach the same level of achievement of the prioritization features (Table 2). In addition, GI in the SUC scenario would have the poorest ecosystem condition (average probability of a favourable habitat conservation status is only 0.09), as expected since the selection of areas under a poorer ecosystem condition was explicitly coerced by the spatial constraint of this last scenario. The S4P scenario, which favours the selection of PU close to populated areas, resulted, on average, in a value of ecosystem condition closer to the SIN scenario (Table 2).

The small irreplaceable area for the SIN scenario shows that there are many alternative solutions to establish GI, since only 8000 km^2 (80 PU) were selected in more than 90 runs (Table 2). Irreplaceable area in S4P and especially in the SUC was notably larger given the spatial constraints imposed in these two scenarios, which drive the selection frequency towards the preferential areas. Some exceptions can be found in the S4P scenario, where areas in sparsely populated countries (such as Estonia, Latvia and Lithuania) were selected in spite of the spatial constraint used (areas in orange, Fig. 3). The selection of these areas suggests that the multi-functionality provided by PU in these countries is unique within the EU (mainly due to the suitable land uses for threatened birds present in these countries), and cannot be found near populated areas (S4P scenario).

In the case of the SUC scenario we can also identify areas under poor condition that were not selected because they would not significantly contribute to fulfil the required level of representation of prioritization features (areas in blue, Fig. 3). In contrast, some areas are especially important because they present high selection frequency despite good ecosystem conditions (areas in yellow in Fig. 3). For instance, the yellow patch in Sweden shows a high selection frequency because of the

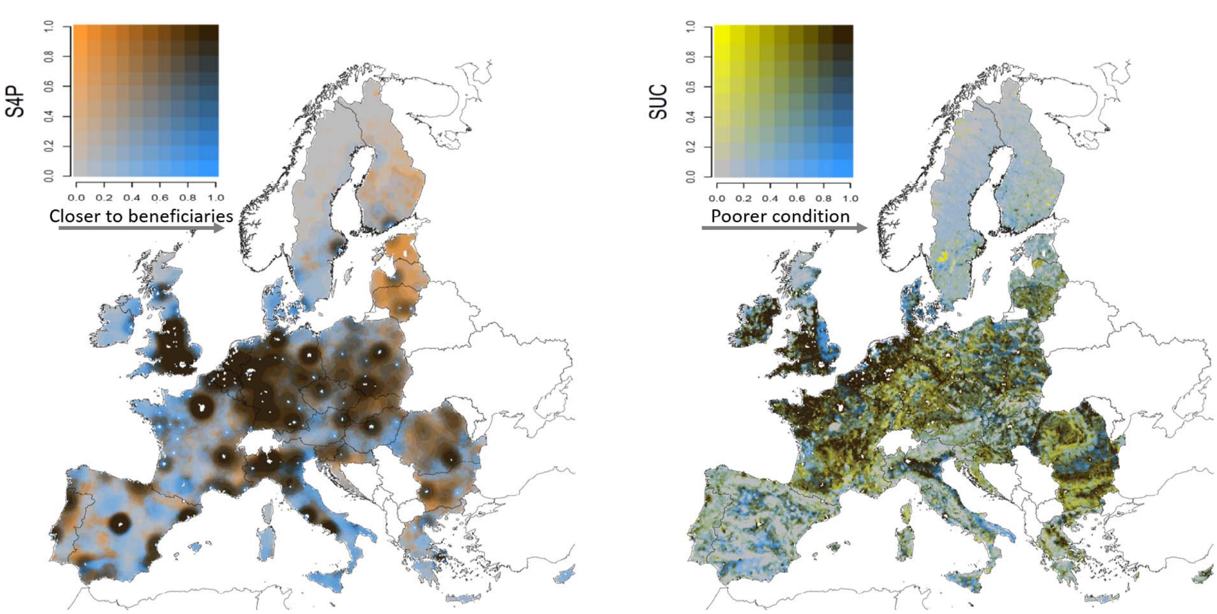

Fig. 3. Selection frequency in the 'Services for people' and 'Services under concern' scenarios against the spatial constraint used, favouring the selection of areas closer to beneficiaries and under poorer ecosystem condition respectively. Axes values represent the 10% quantiles of each parameter. Areas in white within the EU territory correspond to the planning units with a share of artificial areas above 50% that were excluded from the spatial prioritization.

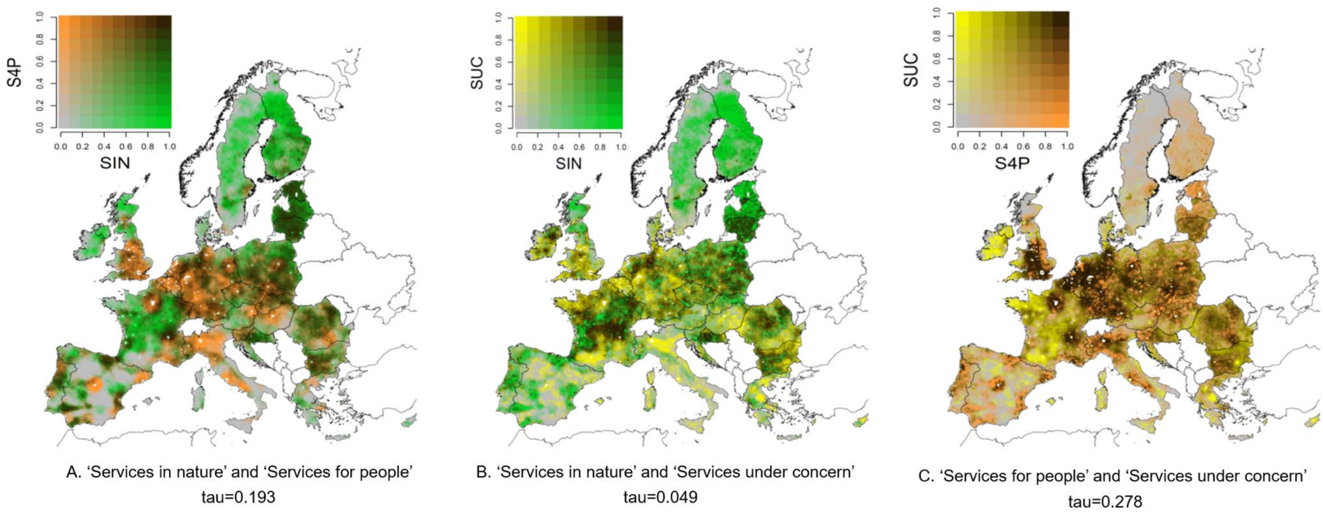

Fig. 4. Pairwise comparisons of the selection frequencies (i.e. how irreplaceable that planning unit was to accomplish the required level of the prioritization features) for the different scenarios: 'Services in nature' (SIN), 'Services for people' (S4P) and 'Services under concern' (SUC). Axis represent the 10% quantiles of the selection frequency. The Kendall rank correlation coefficient (tau) between scenarios is also given.

importance of this area for amphibians.

The relative contribution of the prioritization features in the irreplaceable areas shows that in the SIN scenario the irreplaceable area is mainly concentrated in farmland habitats. In this scenario, nursery habitat for threatened birds (mostly farmland species), for farmland common birds; and potential pest control show the largest contribution (Table 2).

After including spatial constraints (S4P and SUC scenarios), the irreplaceable areas are notably larger and nursery habitats for amphibians of conservation concern, net ecosystem productivity and water retention become, on average, the most important features in terms of relative representation. Therefore, if the irreplaceable area of the S4P scenario is chosen for GI designation, there might be an under-representation of multi-functional farmlands. It is important to note here that irreplaceable areas include only the most important areas (selected in more than 90 runs) to meet the required level of prioritization features. However, it does not mean that all ES are properly represented there. For instance, pollination and nursery habitats for mammals of conservation concern are the least abundant in the irreplaceable areas across the three scenarios, with an average percentage of representation of about 7 and 8%, respectively. This means that their availability is more widespread and their representation more easily achievable when searching for a solution for spatial planning of GI.

3.1.2. Pairwise comparisons among scenarios

Pairwise comparisons of the selection frequencies for the different scenarios highlight synergies and conflicts between the different spatial solutions identified (Fig. 4). For instance, the selection frequency of the SIN plotted against these of the S4P scenario (Fig. 4A) depicts in green priority GI areas where only few people benefit from GI; while areas in orange are prioritized for GI designation because they are close to many beneficiaries. In dark brown are areas that are important under both scenarios. By comparing all three maps (Fig. 4), we identified some regions with high selection frequency in all three scenarios, for instance Lithuania, North of Croatia and Bulgaria.

The correlation analysis of the selection frequency between scenarios shows that the S4P and SUC are the most similar ones (tau = 0.278), given that the share of urban areas is also a pressure included in the ecosystem condition. The S4P and SUC scenarios also show the largest overlap of best solutions (Fig. 5). In contrast, the SIN and SUC scenarios show the weakest correlation for the selection frequency suggesting larger conflicts when planning to maintain ecosystem services in these two scenarios (Fig. 4).

3.2. Case study: cost-effectiveness of invasive species control

The cost-effectiveness assessment confirms that costs of invasive species control per hectare are higher for the 'best solution' of the S4P and SUC scenarios as compared to the SIN scenario (about 14% and 18% higher cost for the S4P and SUC scenarios respectively, Table 3). In spite of having the highest cost per hectare, the SUC scenario yields the largest effectiveness-cost ratio (Table 3). In this scenario, selection of areas under poor ecosystem condition was favoured, but it does not necessarily mean that the level of invasion is high everywhere. For instance, areas in Ireland were prioritized because of the relatively poor ecosystem condition (Maes, 2013). However, these areas have a moderate level of invasion (Chytrý et al., 2009), contributing to a higher effectiveness after simulating the measure of invasive species control.

Differences in cost-effectiveness among scenarios become larger when the population benefitting from restoration measures is taken into account. The S4P scenario becomes the most cost-effective given the large population that would benefit from the restoration measure, followed by the SUC scenario.

4. Discussion

Although the spatial GI network typically serves many purposes and functions, the actual designation and deployment of GI depends on specific policy or project objectives. The optimal allocation of new GI in a landscape therefore calls for an evaluation of different spatial planning solutions (Madureira & Andresen, 2014). In this study, we have developed a prioritization framework, taking a step forward towards the support of the designation of GI. In particular, we addressed the multi-purpose nature of GI by assessing different spatial planning solutions depending on specific goals to be achieved. Our alternatives for spatial planning of GI were based on different types of relationships between ecosystems and socio-economic systems, where ecosystem service potential, beneficiaries (i.e. the human population) and drivers of change (i.e. ecosystem condition) were taken into account by means of spatial conservation prioritization.

Our results, based on an EU-wide analysis, could be used to guide policy decisions on GI investments at the EU level, depending on the policy scenario potentially adopted. In this sense, comparisons between scenarios have shown that important areas for ecosystem service potential can also be found near urban areas in the EU. Contrary to our expectations, the total required area for GI designation was approximately equivalent in both the S4P and the SIN scenarios (Table 2). This

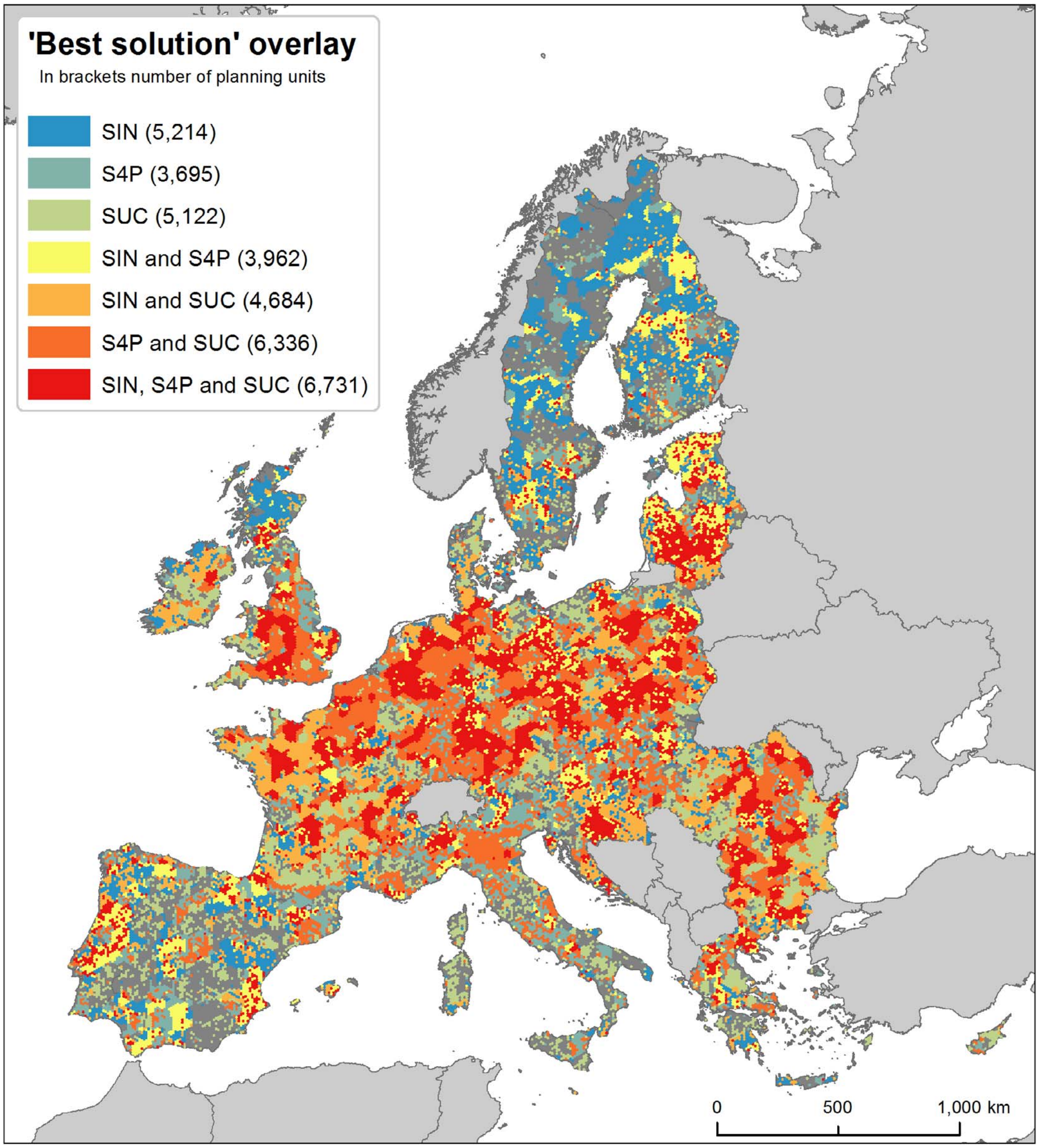

Fig. 5. Overlay of the 'best solution' of the three scenarios used for the spatial selection of the GI network: 'Services in nature' (SIN), 'Services for people' (S4P) and 'Services under concern' (SUC). The scenarios overlay is given for all possible combinations.

Table 3
Cost-effectiveness assessment of invasive species control in the 'best solution' of each scenario: 'Service in nature', 'Service for people' and 'Services under concern'. Effectiveness[1] and cost[2] values are expressed per hectare to be restored. Two cost-effectiveness indicators (dimensionless) were calculated: effectiveness-cost ratio (effectiveness/cost) and the per capita effectiveness-cost ratio (PC effectiveness/cost).

	Effectiveness/ha	Cost/ha (€)	Beneficiaries/ha	Effectiveness/cost (dimensionless)	PC Effectiveness/cost
'Services in nature'	1.29	932	1.40	1.38	1.17
'Service for people'	1.42	1058	2.07	1.34	1.38
'Services under concern'	1.56	1100	2.09	1.42	1.21

[1] Effectiveness: changes in the probability of favourable conservation status weighted by the extent and the level of invasion (see Eq. (2)).
[2] Cost: based on the average cost of 901 € per hectare and weighted by the extent and level of invasion (see Eq. (3)).

demonstrates that, per unit area, peri-urban areas have an equivalent ES potential to more remote areas; suggesting that GI might also be efficiently established in the proximity of urban areas. However, as illustrated by the removal of invasive alien species, restoration costs in peri-urban areas were higher as a result of poorer ecosystem condition. Although prioritization of GI in urban areas was not considered in this study due to the relatively coarse scale of analysis, they are very important to enhance the benefit derived from ecosystem services to people. Therefore, prioritization of urban GI should be considered in future studies at a finer spatial scale, to integrate all relevant elements and services at an urban level.

The larger extent of GI required under the SUC scenario, as compared to the other two scenarios, confirmed that areas in poor ecosystem condition (i.e. measured here as the probability of favourable habitat conservation status) have a lower ecosystem service potential per unit area. This finding is in agreement with the results of Maes et al.

(2014) and also supports the use of the improvement in habitat conservation status as a proxy for the effectiveness of the restoration measures on ecosystem services.

We provide an EU-wide spatial prioritization for GI that could be taken as a first step of a nested approach in which each scale provides context for the scale below, providing in this way the most effective arrangement (Gilliland & Laffoley, 2008). Certainly, the prioritization framework we have presented here can be applied at a country or regional level to support local planning. However, it may be expected that spatial prioritization solutions differ among spatial scales since results will be driven by the distribution of an ES within the study area; whether it is widespread or more spatially restricted.

In our attempt to quantify cost-effectiveness of invasive species control at the EU level, it was quite difficult to determine where removal of invasive species would be most cost-effective. The answer largely depends on how cost-effectiveness is defined, with or without the beneficiaries' perspective. If the final goal of designating GI and ecosystem restoration is to contribute to human well-being, beneficiaries should be considered (Zorrilla-Miras et al., 2014). When accounting for the cost-effectiveness in *per capita* terms, using the removal of invasive species as an example of restoration action, the GI identified by the S4P scenario were the most effective, given the large share of the population that would potentially benefit from ecosystem restoration. This supports the vision that the implementation of ecosystem restoration may contribute to improving multi-functionality while providing increased benefits for society. In turn, it can be expected that an approach based on enhancing benefits for people may result in more financial incentives for restoration (Adame et al., 2014). However, it is important to bear in mind that ecosystem restoration implemented closer to people, or in areas which have unfavourable ecosystem conditions, will likely fail to bring ecosystems to the same favourable status as natural ecosystems (Benayas et al., 2009; Schneiders, Van Daele, Van Landuyt, & Van Reeth, 2012).

The methodology used for the cost-effectiveness assessment presents a number of limitations given the assumptions made with respect to the level of invasion (see Section 2): the higher the invasion level, the more expensive and the less effective the restoration measure will be. Although this assumption has an ecological basis, more evidence is necessary to support it and to improve our assessment. Based on the negative relationship between the presence of invasive species and habitat conservation status (Maes, 2013), we assumed that removing invasive species improves habitat conservation status and that this improvement has a positive impact on ecosystem services (Maes et al., 2012). However, the role of removal of invasive species may have a variable influence depending on the ecosystem service type (Dickie et al., 2014).

The cost-effectiveness assessment illustrates some of the trade-offs that arise when multiple options to designate GI are available. Win-win situations are possible, however, where different alternatives meet their goals (Chan et al., 2007), as in the 'best scenario' overlay (Fig. 5).

4.1. Different priorities for ecosystem management?

Our results show that important areas for the enhancement of ecosystem service potential are widespread across Europe. Consequently, many different approaches can be used to set spatial priorities for GI designation. This was evidenced by the relatively small irreplaceable area for the SIN scenario and by the large influence of the spatial constraints on the final allocation of the irreplaceable area in the S4P and SUC scenarios (Fig. 2).

Although we included some ecosystem services directly related to biodiversity (i.e. nursery habitats for different groups of species), a less flexible solution would have been obtained by including the species distribution ranges separately, as done in other studies specifically focussed on biodiversity and threatened species (Lung, Meller, van Teeffelen, Thuiller, & Cabeza, 2014; Venter et al., 2014). Higher selection frequency would have been assigned to those areas where species distribution ranges are smaller because of the limited spatial representation of these ranges across the EU-28. Comparison of our results (i.e. the 'best solution' overlay for all scenarios, Fig. 5) with other studies identifying important conservation areas for threatened species (Hermoso, Clavero, Villero, & Brotons, 2016; Lung et al., 2014; Venter et al., 2014) shows rather opposing findings. Most areas prioritized in our study for GI designation, especially by the S4P and SUC scenarios, are very different from the priorities identified in the studies based on threatened species only (most of them with restricted distribution ranges).

This lack of spatial match at the EU level between conservation of threatened species and important multi-functional areas (while benefiting society) stresses the need for an ecosystem-based management system that takes into account the gradient of land-use intensity (Schneiders et al., 2012). Areas which are characterized by low land-use intensity and high biodiversity values (in the sense of Lung et al. (2014) and Hermoso et al. (2016)) have a high capacity to deliver ES as well, especially regulating and cultural services (Chan et al., 2011; Schneiders et al., 2012). In these areas, by conserving and/or restoring biodiversity, some ES are also indirectly enhanced (Cimon-Morin, Darveau, & Poulin, 2013). However, with this study we shifted the focus towards areas of higher intensity of human use (either those in peri-urban areas in the S4P scenario, or with poor ecosystem condition in the SUC scenario), where the overall supply of ES becomes more important (Schneiders et al., 2012), especially when considering their large demand. Improvement of the ecosystem condition and investments in GI in these areas may create extra opportunities to bring their ecosystems closer to the conditions of natural areas, which, in turn, would make them more suitable for specific threatened species and increases their biodiversity value (Schneiders et al., 2012).

5. Conclusions

The European Commission in its GI strategy underscores the multiple purposes that GI serves with respect to achieving different policy targets (i.e. biodiversity, human well-being, green economy). Our study shows that the design of an EU-wide GI network depends heavily on policy priorities. Under the scenario of a limited budget, a network designed to deliver ecosystem services mainly as benefits to people will have a different spatial configuration than networks planned to achieve favourable habitat and species conservation status as required by the Habitats Directive. There is unlikely to be a single, cost-effective solution that fits all the different objectives formulated in the EU GI strategy given a realistic budget. Still, an exercise such as that presented in this study can help define priority areas. Given the scarcity of resources for investment in GI and ecosystem restoration, win-win situations should be identified where GI development can deliver several policy objectives simultaneously.

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Appendix A.

See Figs. 6 and 7.

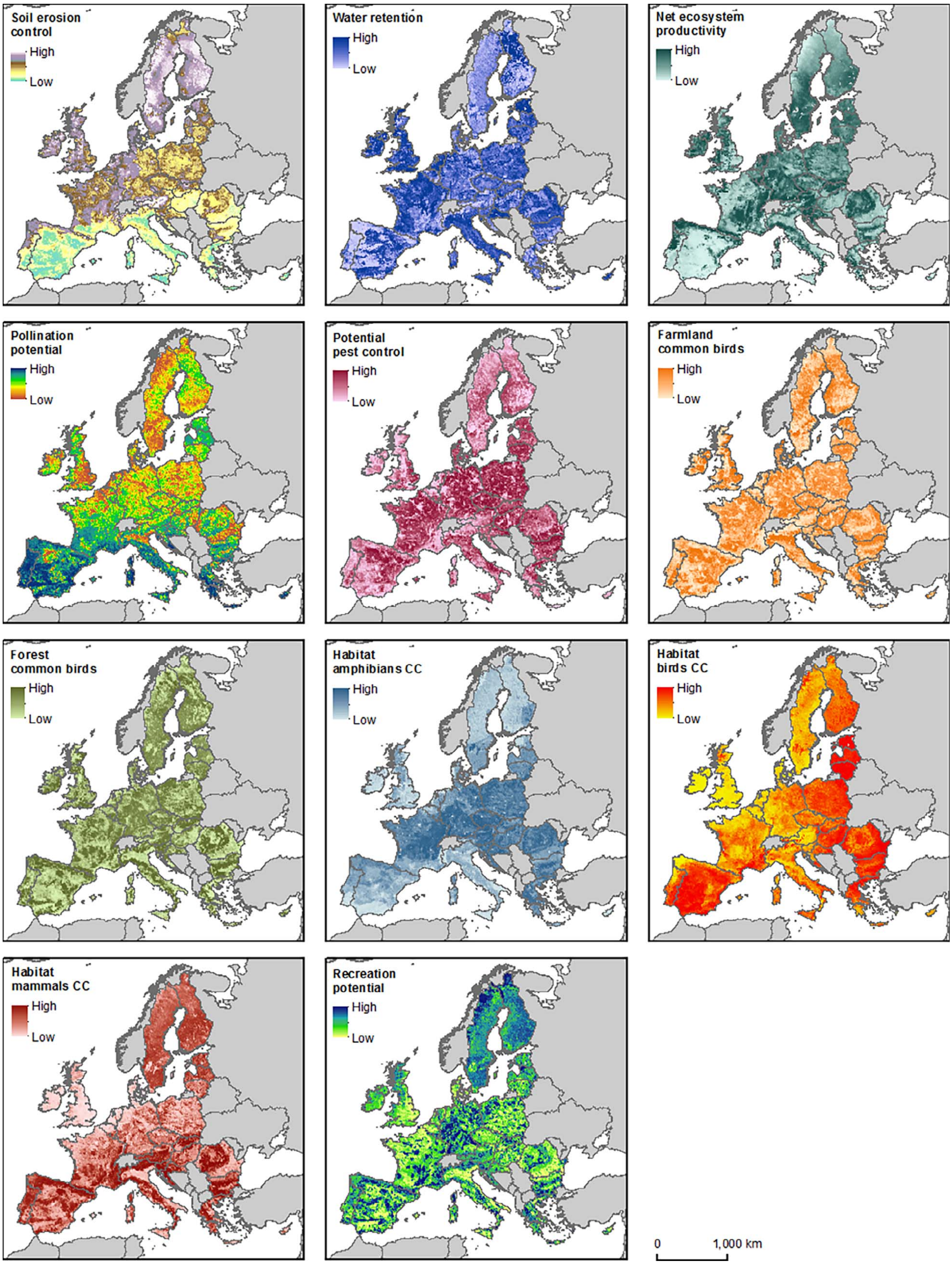

Fig. 6. Maps of the ecosystem services used as prioritization features.

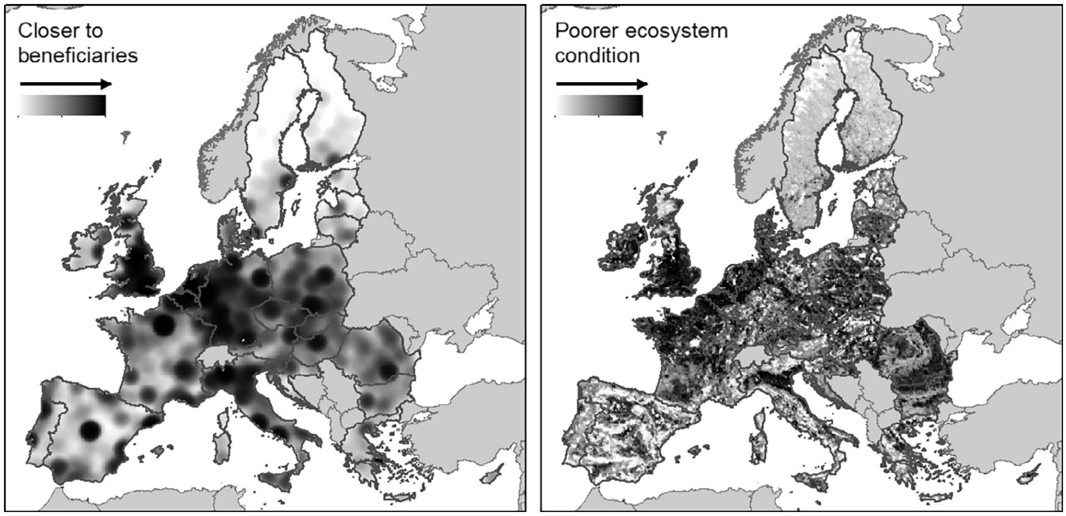

Fig. 7. Spatial constraints used for the 'Services for people' and 'Services under concern' scenarios, favouring the prioritization of GI designation closer to services beneficiaries and under poorer ecosystem condition respectively.

Appendix B.

Table 4.

Table 4
Land use categories of the EU Reference Scenario used to assess the ecosystem service potential. The correspondence with the Bioscore data based on Corine Land Cover classification is also shown.

Reference Scenario	Bioscore – Corine Land Cover
Urban fabric	Continuous urban fabric
	Discontinuous urban fabric
Industry and related uses	Industrial or commercial units
Infrastructure	Road and rail networks and associated land
	Port areas
	Airports
	Mineral extraction sites
	Dump sites
	Construction sites
Urban green leisure	Green urban areas
	Sport and leisure facilities
Arable	Non-irrigated arable land
	Permanently irrigated land
	Rice fields
	Annual crops associated with permanent crops
	Complex cultivation patterns
	Land principally occupied by agriculture, with significant areas of natural vegetation
Permanent crops	Vineyards
	Fruit trees and berry plantations
	Olive groves
	Agro-forestry areas
Pastures	Pastures
Forests	Broad-leaved forest
	Coniferous forest
	Mixed forest
Natural land	Natural grasslands
	Moors and heathland
	Sclerophyllous vegetation
Transitional woodland-shrub	Transitional woodland-shrub
Other nature	Beaches, dunes, sands
	Bare rocks
	Sparsely vegetated areas
	Burnt areas
	Glaciers and perpetual snow
Wetlands	Inland marshes
	Peat bogs
	Salt marshes
	Salines
	Intertidal flats
Water bodies	Water courses
	Water bodies
	Coastal lagoons
	Estuaries
	Sea and ocean

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