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Enhancing Connectivity Improving Green Infrastructure

Cost-benefit solutions for forest and agri-environment A pilot study in Lombardy

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Abstract
Enhancing Connectivity, Improving Green Infrastructure
This pilot study over Lombardy addresses the cost-effective spatial development of a well-connected Green Infrastructure (GI) relevant to the integration of forest, agri-environment and regional development policies. The structural continuity and functional connectivity of semi-natural vegetation, as recommended component of the GI, are assessed. Corridors most favourable to species dispersal are mapped and gaps in connectivity are identified. Spatially explicit solutions are then proposed to prioritise improvement actions based on their monetary cost through payments of 'greening' subsidies and their benefit for connectivity. This is demonstrated at micro-scale to benefit pollinators and pest predators and at regional scale to benefit 'connectivity sensitive' terrestrial species.

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Executive summary

The Green Infrastructure (GI) Strategy, adopted by the Commission in 2013, sets the frame to integrate and strengthen the coherence between different policy sectors and objectives to cope with the increasing competition and intensification in land uses for infrastructure, agriculture and forestry. This pilot study is a contribution to the policy goal of mapping GI as a "*strategically planned network of natural and semi-natural areas"* to better sustain ecological services, to increase the connectivity of ecosystems, and to *"provide ecological, economic and social benefits*".

The focus is on connectivity, a recommended functional attribute of the GI that is essential for the mobility and dispersal of organisms. Under this perspective, forest, 'trees outside the forest' and other natural and semi-natural vegetation features in a region are potentially part of the GI when connected, and their role in enhancing the overall connectivity must be assessed. The landscape-based approach that is applied is in line with matrix management practices that are gaining momentum in regional programs for rural development, sustainable land use, and land use planning.

Spatially-explicit tools and methodological guidance are provided to support policy makers and land managers towards the spatial development of a well-connected GI. Criteria of key importance are on the structural continuity, the surroundings mosaic pattern and functional micro and macro connectivity of semi-natural vegetation. Corridors favourable to species dispersal are mapped and gaps in connectivity are identified. Spatially-explicit solutions are proposed to prioritise improvement actions based on their monetary cost through payments of 'greening' subsidies and their benefit for connectivity.

This GI spatially-explicit priority frame can facilitate and thus encourage the cooperation between advisory and service organisations of the agricultural and forestry sectors as well as between farmers and forest owners. Resulting corridor maps can support the forest sector on targeting areas where to limit intensive forestry practices, where preferably promoting practices in line with species requirements, where privileging more forest conservation than accommodating interests of sectors such as bio-energy. In agricultural lands, the proposed spatially-explicit solutions can support the prioritisation of improvement actions (i.e. individual or collective implementation of Ecological Focus Areas) based on their monetary cost, through payments of 'greening' subsidies and their benefit for connectivity. This framework can as well inform a more cost-benefit effective allocation of subsidies and distribution of payments for woodlands development or for Natura 2000 sites.

The consideration of both ecological and economic aspects will allow authorities and land managers to identify the most cost-effective way of spatially targeting forestry and agri-environmental measures, and thus strengthen their coherence. This provides platform to facilitate the integration of forest, agri-environment and regional development policies. Moreover, the approach of the current study can easily be customised for GI in urban settings.

Methodological guidelines applied on a pilot region

In order to test the methodology, Lombardy (Italy) was identified as a pilot region, being representative of a wide range of landscapes, i.e. agrarian intensively used and fragmented landscapes in the plains, mixed natural and intensively used landscapes in the Alpine foothills and predominant natural landscapes in the highlands. The modelling framework available at JRC is based on GUIDOS Toolbox, Conefor software and Python programming language) and was adapted for GI applications. First, a new high resolution input data to the model suitable to capture small potential GI elements i.e. riparian forest, hedgerows, grassland strips was prepared.

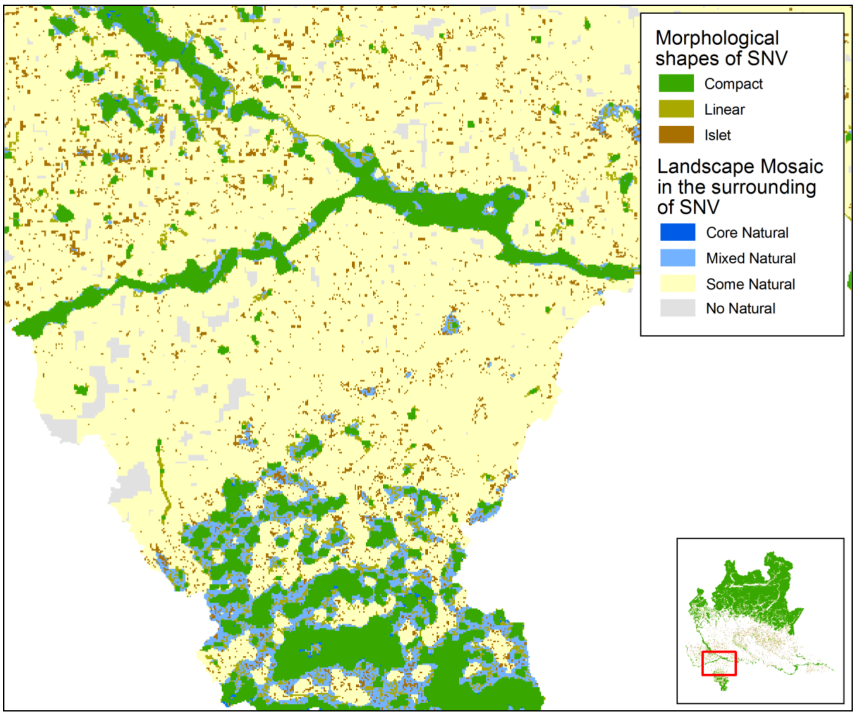


Figure I. Potential Green Infrastructure based on hectares with medium to high natural vegetation share (SNV) in Lombardy, its morphology and landscape mosaic pattern in its immediate surroundings

Potential GI elements were identified, as hectares with medium to high shares of semi-natural vegetation. Their structural continuity was analysed after identifying *networks* made of *compact* and *linear* elements and disconnected *islets*. Their immediate surroundings were characterised according to landscape mosaic patterns, defined with vegetation shares representative of fragmented landscapes. Finally, functional corridors which boundaries were delineated from paths with low to highly probable species dispersal lead to the identification of GI components; lastly, the creation of new connecting paths by converting agriculture to semi-natural vegetation was analysed, in view of enhancing GI connectivity, based on benefit and the monetary cost. This is defined as the loss of income from agricultural output that farmers should be compensated for by the society to replace cropped area with semi-natural vegetation. Then, a new cost/benefit index was developed for decision-makers to strategically select optimal paths based on economic and ecological criteria.

Results show that 25% of Lombardy was covered by semi-natural vegetation, of which about 60% woodlands and 40% other semi-natural lands like grasslands; the structural continuity of vegetation resulted relatively high with 95% distributed as potential GI *networks* (including 10% of connected *linear features)* and only 5% as *islets* (Figure I). Woodlands appeared less fragmented and more linear than other semi-natural lands. Potential GI *networks* in a core natural landscape were mainly found in the northern alpine zone. Nearly one third of the Region, in the Po valley, was composed of agricultural lands with low presence (<20%) of vegetation with concerns related to their surroundings to become GI components. Notably, half of the vegetation was embedded in 'only some natural' landscapes and only few *islets* were surrounded by a mixed mosaic pattern with significant share of natural lands.

A macro-functional connectivity analysis of potential GI *networks* was carried out to map corridors and identify gaps of dispersal in Lombardy (Figure II). Ecoprofiles of terrestrial 'connective sensitive' species of medium dispersal capability that are likely to also benefit a large range of specie, were applied: 50 m in artificial, 500 m in agriculture up to 5 km in natural areas.

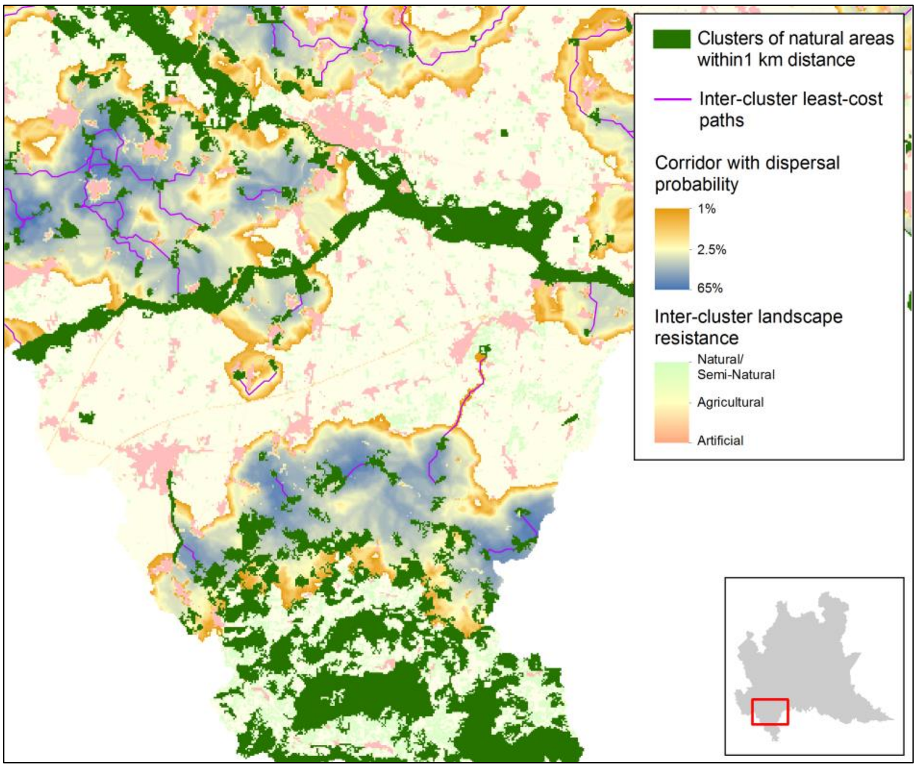


Figure II. Macro-connectivity of potential GI networks showing their clusters and corridors of dispersal in south-west Lombardy. In the centre part of the image, the two disconnected corridors could be connected by restoring vegetation within the agricultural lands; this may be difficult in the right side of the image, due to artificial lands.

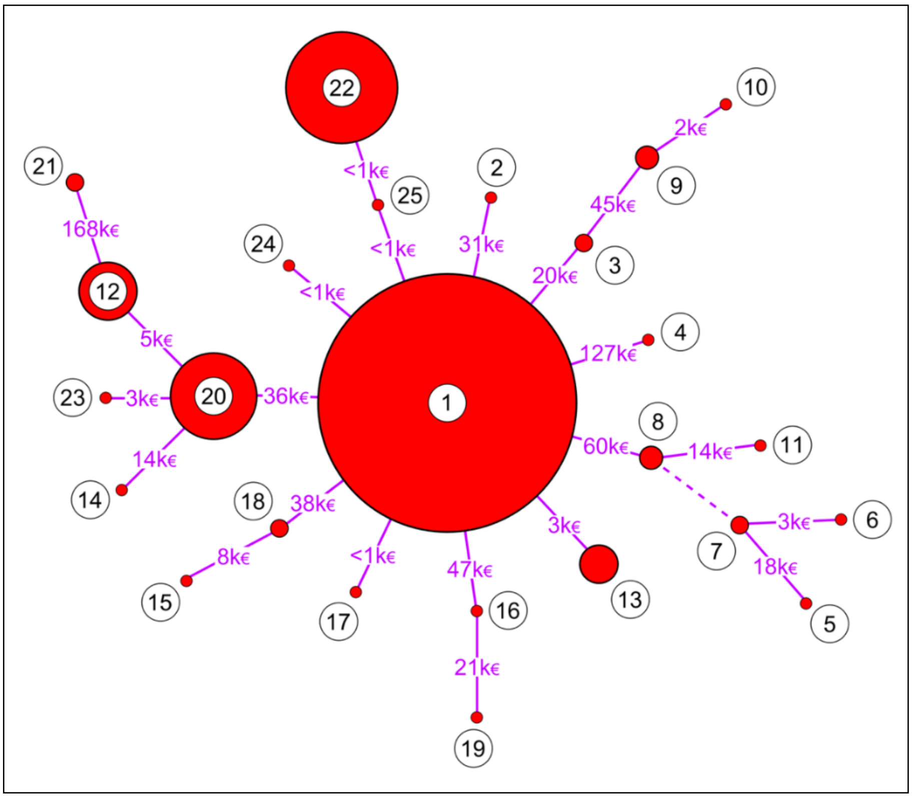


Figure III. Schematic synoptic view of the existing potential GI network in Lombardy, made of 11 'functional' macro-clusters (size proportional to area) and 14 isolated clusters (red dots). To further improve GI connectivity, 24 potential paths (purple links) are identified with the minimum monetary cost involved (k€).

Potential GI *networks* with high vegetation share and when distant less than 1 km, were considered connected and aggregated into '*clusters*'. 238 potential GI *clusters* were identified. Corridors between *clusters* were delineated using the lowest acceptable probability of dispersal of 1% and the maximum found at 65%. 11 'functional' macro-*clusters* were detected while 14 *clusters* were isolated (probability below 1%).

To improve the connectivity of GI in the region, 24 new paths were identified which could become functional by converting a minimum agricultural area into vegetation for an average cost per unit area between 100€ and 2,500€ (Figure III). From those, four paths had the best cost-benefit value. A new schematic synoptic view of the existing potential GI *networks* and their cost effective potential development was proposed as a tool to support decision-makers, particularly to prioritize subsidies at the best cost/benefit places, and thus adapt their amount on the basis of the minimized loss of agriculture in other areas, and to motivate land owners (Table I).

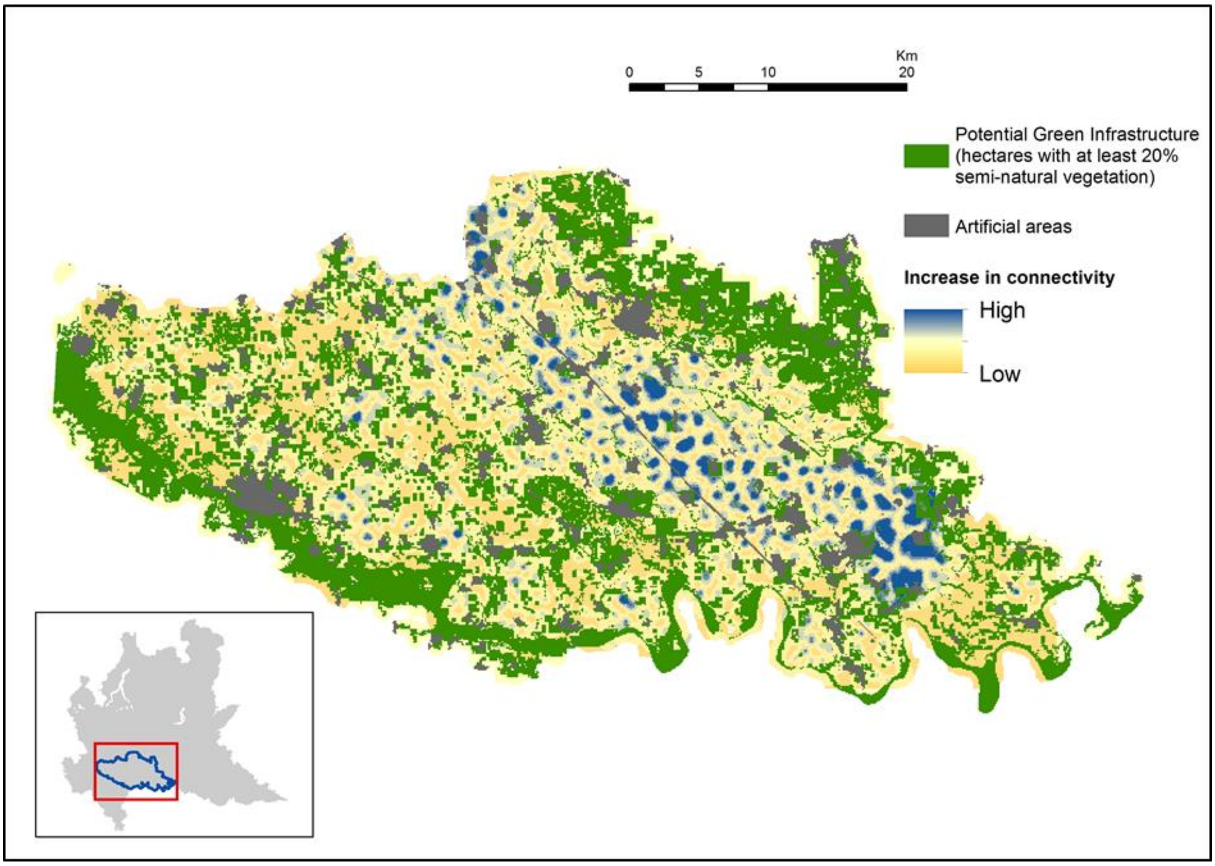
Table I. Cost-benefit analysis showing the 4 best paths to be created between macro-clusters, and the path (6 to 7) which had the lowest cost-benefit value.

Macro-clusters Id code	From	1	1	1	22	6
	To	13	20	25	25	7
Current connectivity value of path		55391	48442	34714	35869	35270
Missing connectivity to be functional		22172	15223	1495	2650	2051
New vegetated area to be created		394	270	26	47	36
Average monetary cost involved		106 €	2,145 €	185 €	115 €	1,498 €
Total monetary cost of functional path		2,611 €	36,281 €	307 €	339 €	3,414 €
Connectivity benefit		0.0013	0.0318	0.0006	0.0005	0.0000
Cost-benefit index		3159	75896	1471	1320	0.02

The micro connectivity analysis was carried out at a sub-regional scale on an intensive cropped area. Potential GI elements were identified as hectares of arable land with a minimum share (~20%) of semi-natural vegetation, above which cropped land is able to support biodiversity and ecosystem services like pollination and pest control.

To improve the connectivity of GI for pollinators and beneficial predators (flying range of 200 m up to 500 m), two scenarios were defined, by simulating the conversion of agricultural cells with low vegetation to GI cells by increasing their vegetation share up to 20%: 1) a "minimum effort" that hypothesizes the conversion of only agricultural cells already close to this threshold, and 2) an "optimal scenario" whereby the minimum number of agricultural cells is converted to achieve a fully-connected network (Figure IV). In each case, the contribution of each new GI cell to the network connectivity was computed together with the cost associated to it, assumed equal to the loss of gross agricultural margin incurred. A cost/effectiveness value was then associated to each potential new GI cell defined as the increase in connectivity per unit of cost.

The analysis allows to target agri-environmental or greening measures according to objectives, such as: I) prioritisation of target areas according to cost/effectiveness; II) minimization of loss of agricultural land/production; III) achievement of a pre-defined level of connectivity minimizing the costs; IV) maximization of connectivity. Results also allow identifying cluster areas where collective implementation of measures by groups of farmers and foresters would be effective.



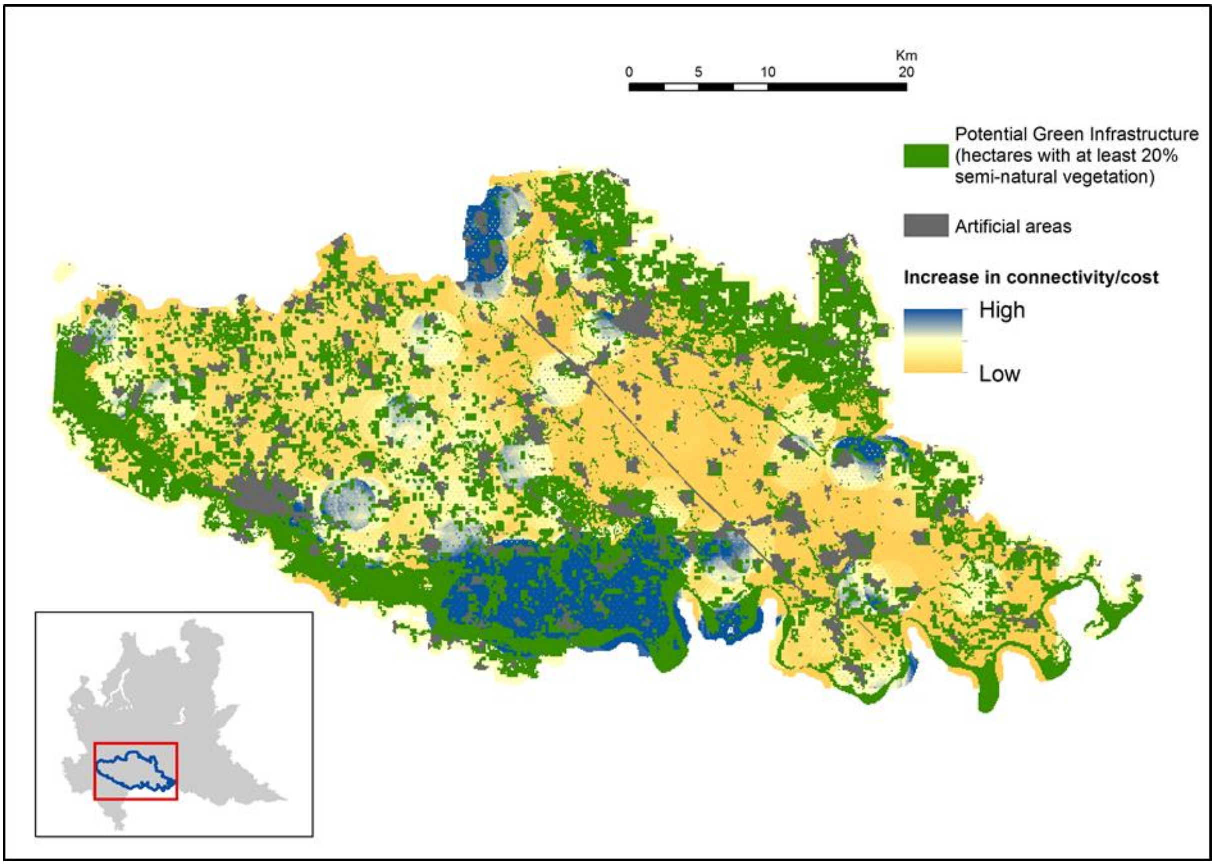


Figure IV. Micro connectivity analysis of potential GI made of hectare cells with low to high vegetation share for pollinators and beneficial predators, showing the contribution of potential new cells to enhance the whole network connectivity (upper figure) and the connectivity increase per unit cost (lower figure)

1 Introduction

1.1 Policy context

In Europe, the erosion and fragmentation of the natural capital constitutes one of the biggest threats to biodiversity, with consequences on the functioning and resilience of ecosystems, including species dispersal and the spread of alien species and pests. Changes in landscape pattern modify the capacity of ecosystems to sustain ecological services like habitat provision, disturbance and climate regulation. Furthermore, the intensification of forestry and biomass production (including wood for energy needs) and the competition for land for urban areas and infrastructure development (transport, markets, energy and mining) are very likely to increase during the remainder of 21st century, thus increasing the need for nature conservation (European Environment Agency, 2016).

Two main objectives of the EU Biodiversity Strategy to 2020 (European Commission, 2011) are (1) achieving a sustainable forest and agriculture for Europe and (2) establishing a Green Infrastructure for Europe to increase biodiversity, enhance ecosystem services and improve human well-being. The European Commission defines 'green infrastructure' (GI) 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).

The GI Strategy adopted by the Commission in 2013, is first a political process of raising awareness and calling for multi-sectoral integration; it is to be "*a successfully tested tool to provide ecological, economic and social benefits through natural based solutions*". The provision of GI is a key policy response to help planners and managers to prioritize actions to maintain, protect and restore ecosystems. GI offers the frame to integrate and strengthen the coherence between policy objectives of multiple sectors. GI will help overcoming the fragmentation of ecosystems (Liquete et al., 2015; Maes et al., 2015) and increasing the connectivity of GI elements in the landscape. Tools and methodological guidance are needed to map, measure and monitor GI landscape elements at multiple scales. Connectivity and GI are gaining a prominent role also when transposing the Habitats and Bird Directive (European Commission, 1992 and 2009). Legal tools are mainly focussing on the adequate management and enhancement of the structural continuity and functionality of linear landscape elements that may act as connectors i.e. livestock trails, rivers, riparian forest, hedgerows, and as support to an improved delivery of ecosystem services i.e. habitat provision, pollination, natural pest control.

Forest and green infrastructure

Forests cover about one third of the EU territory and have a crucial role in dealing with the challenges of climate change, and in sustaining species and biodiversity conservation. For the public, they are the most conspicuous representation of the GI and nowadays, the value of forest ecosystem goods and services is more and more recognized (European Commission, 2013).

According to the European Commission (2010 and 2013) and the European Environment Agency (2016), the integration of GI into the forest sector include three main points and priorities: (1) limiting intensive forestry practices within the limits of GI, (2) setting forestry practices in line with species requirements and (3) the need for the forest sector to 'go outside the forest', develop an ecosystem based approach and accommodate interests of multiple sectors such as agriculture and rural development, bio-energy, plant-health and pest control, climate. Maintaining harvest rates below production is a necessary condition that is traditionally used for forest sustainability but this ratio does not capture whether or not the forest is managed for biodiversity and benefit GI. The spatial patterns of the intensity of forest management, particularly in commercially managed forests due to rotation, are as important as the patterns of afforestation and deforestation in the landscape; they all have an influence on species behaviour, forest composition, structure and function and they may or may not enhance GI. Trends on the change of spatial patterns and the connectivity of woodlands in the European landscapes were recently reported in Forest Europe, 2015. Two thirds of European forests were found in a core natural landscape pattern. In the period 2000-2012, this pattern tended to increase, suggesting local defragmentation processes (natural expansion of forests or newly planted forests). In most countries, the number of landscapes with highly connected forests either remained stable or decreased, suggesting that distance and landscape permeability in between forest areas are not adequately accounted for in management and planning. 35% of European forests were found significantly fragmented by agriculture and artificial lands. At broad scale, landscapes with poorly connected woodlands represented more than 60% of EU territory.

The successful integration of GI into the forest sector depend strongly on the understanding and motivation of forest owners. The different perception (and use) of trees and woodlands depending on countries or regions (Mander et al., 2007) render this integration difficult : production-centered vision in the Nordic forest rich countries, more amenity-driven perspective for recreation, wildlife or human well-being in countries like Denmark or UK, a mixture of different forest uses in Mediterranean countries with intensive timber large exploitations as well as small-scale non-industrial woodlands, often supported by subsidies in rural areas. Private ownership and small size of private holdings (less than 10 ha and rarely exceeding 100 ha) also render this integration challenging. Knowledge transfer and implementation of sustainable forest management (SFM) principles is easier for large publicly owned forest where forest management plans and certification instruments are more used. Private forest owners which represent more than 60% of Europe's forests (European Environment Agency, 2016) are key players to motivate enhancing GI but they perceive that they are not compensated in monetary terms for the provision of non-market forest services like small-scale forest planting for climate regulation, repository of biodiversity, habitat protection and/or natural pest control. Such services remain largely unvalued in contrast to timber (Forest Europe, 2015) in economic and business accounting, and markets. As a result, they do not invest enough in these services and are more concerned about profitability or by the timing and duration of forest subsidies. Landscape perspective and ecological connectivity concepts are also insufficiently applied in forest management and planning. Reasons mentioned in a recent questionnaire were the difficulty of: coordinating multiple sectors and public bodies with diverse management competences (agriculture, urban, transport) and different planning instruments, taking decisions over scales that usually comprise multiple ownerships, municipalities or even provinces or regions, and the lack of tools and methodological guidance (Saura et al., 2015). The governance of forests in Europe has become increasingly complex and furthermore there is a need of trade-offs between the different priorities of multiple sectors when enhancing GI in the forest sector.

Legislation and other tools are currently available to enhance GI. One major forest land use policy objective (Forest Europe, 2015) is afforestation of agricultural land unsuitable for agricultural use; it is part of the set-aside strategy of the EU common agricultural policy (European Commission, 2010). One million hectares were afforested since 1991. Land abandonment and thus, afforestation are expected to increase over the next 30 years (Renwick et al., 2013) especially in highly fragmented landscapes (Keenleyside et al., 2010). Matrix management practices accounting for ‘trees outside the forest’ are found in regional programs for rural development and land use planning (hedgerows in agricultural lands, and livestock trails). Sustainable land use principles and actions are typically fund and developed at regional scale. They include (I) promoting ecological and green corridors in urban and rural areas and in the transition among both, and (II) designing a corridor network among relevant ecosystems at regional level but also considering trans-border regions. Specific mentions or measures to preserve or promote ecological connectivity are found in Forest Strategies or Plans of different Regions; forest restoration actions particularly promote linear plantations or restoration of riparian vegetation as Natural Water Retention measures. The Forest and Natura 2000 guidelines document (European Commission, 2015) recommend accounting for the surrounding landscape of protected forests and enhancing the connectivity of woodlands in the unprotected landscapes in sustainable ecosystem management and landscape planning. In the last decade, new practices like payments for ecosystem services are being advocated to motivate small-scale forest farming and GI. They are found in the European Agricultural Fund for Rural Development (Council Regulation 1698/2005, particularly under axis 2 for agri-environmental payments, for Natura 2000 payments), the Life+ programme, the European Regional Development Fund and Cohesion Fund. Yet, most of expenditure still goes to 'first afforestation' measures, often with exotic species and there is still an under-spending and thus an under-implementation of forestry measures like tree planting at the edge of agricultural fields or agroforestry. The development of tools and methodological guidance on where are the best cost-effective places to allocate subsidies and where to prioritize small-scale ecosystem improvement actions may help to promote and optimize the use of measures among decision makers, forest owners and practitioners.

Agriculture and green infrastructure

Agriculture accounts for almost half of the EU land surface, therefore plays a major role in a correct GI implementation and functioning. In particular, besides cropped areas, agricultural landscapes contain semi-natural habitats (field margins, tree lines, hedgerows etc.) that are not specifically farmed and can constitute an important part of the GI.

Since two decades, the Common Agricultural Policy (CAP) has introduced environmental concern in the legislation. More recently, the EU Biodiversity Strategy to 2020 in its Target 3 asks the CAP to ensure the sustainability of agriculture, and to contribute to biodiversity conservation and improvement of ecosystem services supply. In European Commission (2013) the roadmap for EU agriculture in support of the GI is set through the following steps:

- preventing land abandonment and fragmentation through direct support for farmers in the first Pillar;
- defining appropriate measures under the rural development programmes in the second pillar, including non-productive investments, agro-environmental measures (e.g. farmed landscape conservation measures, maintaining and enhancing hedgerows, buffer strips, terraces, dry walls, sylvo-pastoral measures etc.), payments fostering the coherence of Natura 2000, cooperation on maintaining valuable field boundaries, and conserving and restoring rural heritage features.

Forestry measures in the Rural Development Program were already presented in the previous section. To date there is no detailed assessment of the contribution of agricultural lands to the GI, nor the identification of which farmland categories may be part of it. According to its definition, High Nature Value farmland constitutes an important part of the GI, it is in fact that part of farmland that supports biodiversity, characterised by extensive farming practices and low negative externalities. In general, the provision of ecosystem services by High Nature Value farmland is high when it comes to those ecosystem services linked to low intensity agricultural production, like landscape aesthetics, outdoor recreation, pollination, genetic resources, soil quality regulation etc. (Paracchini and Oppermann, 2012). An important role is played in this context by semi-natural grasslands, which are characterised by high biodiversity (both floristic and faunistic) and are estimated to be roughly 30% of EU grasslands. The CAP includes options for GI enhancement: under Pillar 1 the Greening package, besides payments for crop diversification, includes payments aiming at maintaining permanent grasslands, and at reaching the minimum target of 5% of the arable and permanent crop area be Ecological Focus Areas. In the view of the legislator, GI in agricultural areas "*will therefore foster a more coherent approach to*

decision-making in relation to integrating ecological and sustainability concerns into spatial planning in the rural and urban landscape". A drawback of Ecological Focus Areas is that in the selection of elements that can be accounted for to reach the 5% target, non-permanent crops are included (catch crops, nitrogen fixing crops), which can be beneficial for climate change mitigation, but do not have a direct impact on biodiversity and connectivity.
Under Pillar 2 the priorities that have been identified include "Restoring, preserving and enhancing ecosystems related to agriculture and forestry". Member States must ensure that 30 per cent of the total European Agricultural Fund for Rural Development contribution to each Rural Development Program is reserved for environment and climate related measures for farmland and forests, and that the agri-environment-climate measure is used throughout their territories (Poláková et al., 2014)
Rural Development Plans may include aspects related to ecological coherence and connectivity. Most regions include the restoration of landscape elements involved in connectivity such as hedgerows, thickets, riverside reserves or areas in-between Natura 2000 sites. Specific measures to improve wildlife species through connectivity can also be proposed. The mid-term review of the CAP in 2017 will provide a possibility to review the EFA options (including raising the target).

Transport and green infrastructure
Habitat fragmentation is recognised as one of the biggest threats to biodiversity and among land use change drivers, transport infrastructure is one of the major factors. The consequences for wildlife and for the Green Infrastructure, of constructing transport infrastructure include traffic mortality, habitat loss, fragmentation and degradation, pollution, altered microclimate and increased human activity in adjacent areas. All these cause considerable loss and disturbance of natural habitats. In addition, roads impose movement barriers on many animals, barriers that can isolate populations and lead to long-term population decline (European Commission, 2010)

Barrier and fragmentation effects caused by roads and railways are more and more considered in land use planning, and barrier mitigation measures are specified in different legal instruments. To support sustainable land use planning, critical areas for defragmentation can be identified on the basis of connectivity analysis and can contribute to the mapping of GI (Gurrutxaga and Saura, 2014; Saura et al., 2015). Priority locations are identified for barrier effect mitigation, i.e. particular locations or road sectors where there is a higher potential conflict between ecological corridors and transport infrastructure. Other ways to avoid the barrier effect is to make infrastructure more permeable to wildlife by means of fauna passages, adapting engineering works or by the management of traffic flows. It is thus of major importance in GI mapping exercise that available transport databases include information of eco-bridges, underpasses and tunnels.

1.2 Concepts of landscape spatial pattern and connectivity

The spatial pattern of natural/semi-natural lands is defined as the spatial distribution of patches of natural/semi-natural lands in the landscape.

Morphological shapes of natural/semi-natural lands provide important pattern information due to their ecological role. Interior areas of large compact patches of natural land cover do not experience strong influences from neighbouring patches of other land cover/use categories, and they provide suitable habitat for interior species. When natural vegetation is not predominant like in a human-dominated landscape, the presence of clumps of natural habitat (islets) in the landscape matter for ecological processes (e.g. pollination in agricultural landscape). Linear strips of habitat enhance the spatial continuity in a fragmented human dominated landscape. Linear features and islets are key features for habitat provision services but are often vulnerable to disappear due to their shape and size. Also natural habitat at edges are more exposed to the penetration of invasive species, pests and aggressive edge specialists.

Landscape mosaic pattern types in the immediate surroundings of a given piece of land are defined on the basis of the presence and dominance of selected land uses. For example, to assess forest fragmentation by fragmenting causes such as transport infrastructure and intensive agriculture, the surroundings of forest lands would be characterised according to the proportion of other natural lands, of artificial and agricultural land uses. Furthermore, fragmenting causes are either anthropogenic or natural in origin, and they shape the landscape in a variety of mosaic patterns that are more or less permeable depending on the similarity between adjacent habitats and with different effects on species. It is important to know the fragmentation pattern of natural habitats in order to identify where mitigating the isolation of natural lands in predominant intensive land uses and where maintaining or developing interior habitat in predominant natural landscape.

The connectivity of natural and semi-natural habitats in the landscape is a combined product of structural and functional connectivity, which is an important characteristic of the GI. When habitat patches are not physically connected (i.e. in other terms, habitat structurally connected and continuous), the distance and the landscape matrix between natural habitat patches play a role in the isolation of habitat patches from a species – functional – perspective. The probability of dispersal of a given species in between patches depends on the species dispersal distance and the varying degrees to which land cover/uses are favourable or hostile (landscape matrix resistance) to its dispersal. Connectivity can be defined as the degree to which the landscape facilitates the movement or dispersal of species and other ecological flows among habitat areas. The lack or loss of connectivity reduces the capability of organisms to move and can interfere with pollination, seed dispersal, wildlife migration and breeding. In the context of GI, hostile lands would be land uses with a low or null presence of GI elements (e.g. intensive agriculture, built urban areas, transport or any grey infrastructure etc.), which constitute main obstacles to the inter-linkages of high quality 'green spaces' of natural/semi-natural lands. For a given landscape or region, connectivity is reported through probability of connectivity indices to characterise the whole landscape or region. Functional pathways or corridors in between habitat patches, are mapped on the basis of the cost of species movements across the landscape and a fixed threshold of cost beyond which dispersal is not feasible. The presence and absence of connecting functional pathways and corridors (including but not restricted to least-cost paths) is identified in between each pair of natural/semi-natural habitat patches.

1.3 Data issues related to land cover and species ecoprofiles

Improving data availability and knowledge sharing on connectivity and ecological coherence is listed among priorities for research and monitoring to support GI implementation.

National forest inventories provide data on forest land uses and status including forest area changes (e.g. area losses and gains) but they do not give an insight on the changes in forest spatial patterns and on forest connectivity that are relevant to GI implementation. The broad-scale European-wide connectivity assessment reported in Forest Europe (2015) was based on European wide land cover data at scale 1:100,000 minimum mapping unit (MMU) of 25 ha (Estreguil and Caudullo, 2015). Such data are not suitable to capture small forested patches and 'trees outside the forest' which have a role to play for connectivity, e.g. hedges, lines or islets of trees in agricultural lands. Fine-scale data are more suitable to identify connectivity pathways and support ecosystem management and planning in the context of GI. A recent study conducted by JRC in collaboration with the Universidad Politecnico de Madrid over a region in the North of Spain (Saura et al., 2015) reported that connectivity is about 20% underestimated when derived from broad-scale data and compared to data at finer scale of

1:25,000 MMU of 2 ha. Broad scale findings like the fact that landscapes with poorly connected woodlands represent more than 60% of EU territory, would then be revised when assessed at finer scale.

Garcia-Feced et al. (2015) mapped natural and semi-natural vegetation (SNV) in agricultural areas, on the basis of remotely sensed images and geospatial data (see 2.4). This includes hedgerows, woodlots, semi-natural grasslands, forest edges. Results are released at 1 km resolution, though the original resolution of hedgerows is 25 m and of semi-natural grasslands is 250 m. Micro-features such as field margins and buffer strips cannot be detected in the analysed imagery.

Under the Copernicus program, a high-resolution layer (20 m) of semi-natural grasslands is under preparation[1]. Semi-natural grasslands are also mapped in the HNV farmland layer (Paracchini et al., 2008), on the basis of Corine Land Cover (CLC) and expert judgement. The resolution of CLC, though, makes this source unsuitable to the analysis presented in this report. No other source is available for linear elements, at least until the layers of Ecological Focus Areas to be prepared under the CAP by Member States will become available.

Another issue of concern is about the selection of species eco-profiles to satisfy multiple sectors in the context of GI. For example in forestry, sufficiently large areas of suitable forest habitat should exist to support a viable population (or meta-population) of forest species like woodpecker or other forest specialist birds, bear, lynx or other large mammals while in other cases, open forest structure would be preferable like in the case of capercaillie. In agricultural land, the presence of hedgerows supports bird populations (Hinsley and Bellamy, 2000), permanent elements of SNV are in general beneficial to a number of organisms, from small mammals to insects like pollinators and pest predators. It is important to note that functional biodiversity (i.e. bees, ladybirds) is important for agricultural production as it provides essential ecosystem services such as pollination and pest control.

There is a lack of precise information on species traits and their response to landscape features. In the context of GI, (Saura et al. (2015) suggested to use only few forest species ecoprofiles that would be representative of a variety of forest habitat types and of the potential species responses to the landscape matrix heterogeneity. Two generic forest ecoprofiles were defined: forest generalist species and the forest broadleaved species, both according to CLC forest canopy cover definition of 30%. Two more specific ecoprofiles were proposed when additional detailed information is available on forest canopy cover, stage of development and tree species: specialist species of mature forest in closed canopy, forest generalist species according to the forest canopy cover above 10% definition of Food and Agriculture Organization (2000). In the case of agriculture, mobile-agents with lower dispersal capabilities such as wild bees and ladybirds have been identified as reference for defining the ecoprofiles.

Landscape changes with the largest effects on connectivity are to be found outside the forest land use; they are permanent and aggressive changes related to transport infrastructure, urban development and to a less extent intensive agriculture. Resistance values for the dispersal of species in those hostile land uses are usually arbitrarily defined. Paths of forest species dispersal depend more on the presence of keys green infrastructure elements such as forest of public utility, riversides and protected areas in the landscape. According to the literature review in Saura et al. (2015), the largest responses to matrix heterogeneity and its changes (e.g. largest increases in connectivity after the mitigation of the barrier effect of roads) are found for the short (200m to 500 m) and for the medium dispersal distances (1 to 5 km) and generally not for the largest ones (10 to 25 km). Short distances

[1] http://land.copernicus.eu/pan-european/high-resolution-layers/grassland/view

are representative of main connectivity patterns, and the 5 km distance is enough to provide a very high or close to maximum connectivity level between key green infrastructure elements in a region.

1.4 Objectives of this study

This pilot study is focusing on the cost-effective spatial development of a well-connected GI in rural sub-national (regional) settings to support the integration of the forest, agri-environment and regional development policy sectors. First, it aims at characterising the landscape mosaic pattern, the structural continuity and functional connectivity of SNV, as such potential “green” terrestrial component of GI. Then, the goal is identifying gaps in connectivity and proposing spatially explicit solutions to prioritise improvement actions for reinforcing the GI, based on their monetary cost through payments of ‘greening’ subsidies and their benefit for connectivity.

This pilot study uses the spatially-explicit and integrated modelling framework that has been developed at JRC and is based on two available free software packages, GIS programming tools and a standardized and easily reproducible set of indices to assess landscape pattern, fragmentation and connectivity of any ecosystems or geographical units over large areas (Estreguil et al., 2014a). This model has been applied over large regions to assess forest at European scale (Estreguil et al., 2012) and also to measure the connectivity of Natura 2000 sites (Estreguil et al., 2014b). Harmonized forest landscape pattern information is generated every four years for the Forest Europe, United Nations Economic Commission for Europe (UNECE) and FAO joint ministerial reporting process on the protection of forests in Europe (Forest Europe et al., 2011; Forest Europe, 2015). It has also been applied at regional scale, the most recent case study being on the connectivity of forest Natura 2000 sites in Spain (Saura et al., 2015). This study included a comparative assessment of connectivity based on broad-scale and on fine-scale data (Saura et al., 2015), which results have supported the launch of the current pilot analysis.

This study aims particularly at testing and customising the JRC modelling framework to support GI purposes; particular attention is paid to select and upgrade appropriate input data to the model on the basis of recently available high resolution layers, and then, to upgrade the connectivity assessment part by mapping corridors in between GI elements, identifying gaps and developing a new cost/benefit index as a tool to guide and prioritise the geolocation of ecosystem improvement actions.

The aim of the proposed methodology is to be applicable throughout Europe, therefore it does not take into consideration ecoprofiles of specific species nor considerations on habitat quality. It constitutes a core methodology potentially applicable everywhere, which can be locally improved, also by using data locally available, to address specific needs.

2 Data

An analysis of GI connectivity is based on the identification of potential GI elements, which are elements – often small in size - of SNV, and the main limitation so far in European-scale studies is the quality of the input data. Corine Land Cover (CLC) is by far the most used land use/cover dataset as it is the only coherent and consistent European-wide dataset. However, its MMU is 25 ha does not allow to detect small elements. This study is based on recently available high resolution layers and put forward a method to combine and integrate them for obtaining a fine-scale data input in models.

In particular, the following datasets have been used and are described in the following sub-sections:

- A refined CLC map elaborated by Batista e Silva et al. (2013)
- A new forest High Resolution Layer under production in the frame of the Copernicus project.

- A pan European high resolution roads layer provided by OpenStreetMap
- A map on the abundance of herbaceous SNV in agricultural land in Europe, developed by Garcia-Fecéd et al. (2014).

Subsequently, the methodology developed to combine and integrate them is illustrated.

2.1 The refined Corine Land Cover map (100 m resolution)

The refined CLC map was developed by Batista e Silva et al. (2013) by integrating more detailed, ancillary datasets into the original CLC layer (release 2006, raster format, 100x100 m cell size, MMU of 25 ha), namely:

- The CLC change map 2000-2006 depicting areas that experienced land use/cover change between the respective pair of years. This map has a MMU of 5 hectares.
- The Soil sealing layer, a dataset produced within the Global Monitoring for Environment (GMES) program by the European Environmental Agency. The layer provides the percentage of sealed soil in a given cell as a continuous value ranging from 0% to 100%. Originally developed at 20x20 m resolution, the final released was aggregated at 100 m resolution.
- The Urban Atlas, a set of high-resolution digital land use/cover maps covering major European urban regions. The Urban Atlas nomenclature is based on CLC, but it is more detailed as regards urban areas, whilst it is less detailed with respect to the other land use/land cover classes.
- The Tele Atlas Spatial Database consisting of a series of digital maps mainly focused on transportation networks for navigation purposes.

A stepwise approach based on a semi-automated protocol with a set of decision rules was applied to obtain a refined version of the CLC layer. The full process is described in Batista e Silva (2013). The result is a layer with the same cell size (100 m) but increased spatial resolution compared to the original CLC map, the new MMU being 1 hectare. The main improvements – validated through comparison with the Land Use/Cover Area frame Survey (LUCAS) dataset - mostly concern artificial areas. The nomenclature is the same as the original CLC, but a thematic refinement was introduced in relation to urban fabric by breaking it down in three categories based on density levels: high-density urban fabric, medium-density urban fabric, and low-density urban fabric (113).

Despite some limitations in the methodology, mainly due to the non-homogeneous level of detail and coverage of the ancillary datasets used, the refined CLC can be considered a significant improvement for the purposes of this work; therefore, it has been used at the starting point for further refinements and elaborations. Henceforth, whenever we mention to CLC as input layer, we refer to this refined version.

2.2 Roads layer (25 m resolution)

The layer was obtained by extracting the road layer of the OpenStreetMap dataset[2], a community project to create free, open data maps of the world. Data is licensed under the Open Data Commons Open Database License. The original layer is in shapefile format (polyline features). It classifies roads in different categories and contains information on road segments classified as tunnels and bridges. For the purpose of present exercise, we selected only the main roads i.e. those classified as motorways, motorway links, primary, primary links, trunks and trunk links. First, main roads were extracted from the database and tunnels and bridges were also removed to obtain road segments

[2] The OpenStreetMap layers are collected, stored and processed by Geofabrik Gmbh. Data are updated every day and can be downloaded from http://download.geofabrik.de

actually fragmenting the habitat. Since the original data is in linear form, we applied a buffer of 12.5 m width around the segments to transform them into areal elements with an average road width of 25 m. This was considered an acceptable approximation of the average width of main roads with two (including not asphalted road verges) and fit to purpose as it is the same cell size as the forest high-resolution layers described below and it's a quarter of 100 m cells. To be processed, the obtained shapefile was then converted to raster format.

2.3 Copernicus Forest High Resolution Layer (25 m resolution)

In the frame of the Copernicus Programme - The European Earth Observation Programme - several pan-European High Resolution Layers (HRL) are being produced under the coordination of the European Environmental Agency. These layers are obtained through processing satellite imagery. They provide information on specific land cover characteristics. The spatial resolution is 20 m or 25 m. Five datasets are under development for the following themes: imperviousness, forest, wetlands, grasslands and water bodies. The forest layers are the most advanced ones: four main products are being developed:

- A first set (Service Element 1) of 2 layers with a spatial resolution of 20 m: tree cover density and forest type.
  - The tree cover density dataset maps the level of canopy cover in a range from 0-100% and has no MMU.
  - The forest type product in turn consists of two products: 1) a dominant leaf type product that has a MMU of 0.5 ha, as well as a 10% tree cover density threshold applied, and 2) a support layer that maps, based on the dominant leaf type product, trees under agricultural use and in urban context (derived from CLC and imperviousness 2009 data).
- A second set (Service Element 2) of two additional products produced for the JRC with a spatial resolution of 25 m. These products are
  - tree cover presence/absence;
  - dominant leaf type.

Currently, Service Element 2 is in a more advanced state of elaboration and validation across Europe (but not fully validated yet) and it is therefore used in present exercise.

The layers have been developed following these technical specifications: the tree cover presence has been mapped such that as a minimum the occurrence of patches of trees on the ground, showing a leaf ground coverage of at least 30% on a contiguous area of at least 50 m in diameter, is detected with a probability matching at least the User's Accuracy of the Tree Cover class. A contiguous area is defined as an area not containing subarea(s) with less than 10% leaf coverage and with a diameter of more than 10m. The dominant leaf type indicates whether the canopy is either broadleaved or coniferous vegetation.

No further processing of Tree Cover Presence/Absence to a Forest/Non Forest mask (e.g. according to FAO definition) is performed. Five lots covering the whole EEA39 countries have been assigned to different contractors. Accuracy assessment was carried out following a standard sampling scheme elaborated by JRC based on a regular grid and a stratified random point sampling approach. Minimum acceptable accuracy was set at 85%. The tree cover presence/absence layer is used for the calculation of share of forest habitat class in the present analysis.

2.4 Semi-natural grassland in agricultural land (100 m resolution)

This layer is derived from the Pan European map of SNV abundance in Europe elaborated by the JRC (García-Feced et al., 2014). This shows the abundance of woody and herbaceous SNV (trees, hedgerows, semi-natural grasslands) in European farmland. The method builds on the analysis of satellite imagery and geospatial data. In particular, the spectral rule-based preliminary classifier (SRC), called Satellite Image Automatic Mapper™ (SIAM™) was used. It consists of a mosaic of space borne multi-spectral images with a resolution of 25 m. The output map legend consists of a set of 59 spectral categories (spectral-based semi-concepts), e.g. “Weak Vegetation”, “Strong Shrub Rangeland” etc.

The final map is the sum of two sub-components: woody SNV and herbaceous SNV. For the purposes of the present work, we used the herbaceous component only, since the woody component is already covered by the forest high resolution layer described in the previous section. The full method and processing used to derive the herbaceous component is described in García-Feced et al., 2014 and is summarised hereafter. Spectral categories matching the target semi-natural land cover classes (grassland) were identified by cross-tabulation against the 100 m resolution CLC 2006 map, by selecting those with the highest occurrence in the CLC classes 2.3.1 “Pastures” and 3.2.1 “Natural grasslands”, and low occurrence in the class 2.1.1 “Non-irrigated arable land”. The herbaceous SNV were defined as *permanent* grasslands managed in an extensive way.

To detect permanent grasslands and remove temporary ones, a phenology-based indicator was developed, by extracting vegetation dynamics from a 250 m-resolution Moderate Resolution Imaging Spectro-radiometer image derived time series (2004–2009) of 10-day maximum Normalized Difference Vegetation Index composites at European scale (Weissteiner et al., 2008). These parameters describe proportions of seasonally changing and permanent vegetation throughout a growing season, including timing of the vegetation peak. Information on aridity provided by the Desertification Indicators System for Mediterranean Europe (Brandt et al., 2003), environmental zoning (Metzger et al., 2005) and olive farming intensity data (Weissteiner et al., 2011) were also used as complementary data to distinguish arable land from stable or permanent vegetation. The resulting phenology-based indicator was discretized into quintiles, such that the 1st and 2nd quintiles were likely to represent temporary grasslands or arable lands and were therefore removed.

To discern between intensive and extensive grasslands, two sources of information were used: the Common Agricultural Policy Regionalised Impact (CAPRI) model (Britz, 2008) and the High Nature Value farmland map (100-m resolution) elaborated by Paracchini et al. (2008). The CAPRI models provides energy input (MJ/ha) in grasslands at the spatial resolution of the so-called homogeneous spatial mapping units (resolution, 1 km) and this indicator was used as a descriptor of management intensity. Energy inputs included in the indicators comprise fertilizer application (organic and mineral manure), machinery and human labour. Again, this indicator was discretized into quintiles for each of the main 12 environmental zones of Europe, and only cells belonging to the first quintile were considered as extensively managed grasslands. As a second source of evidence of the presence of herbaceous SNV, the High Nature Value farmland map (100-m resolution), was adopted. Finally, the CLC classes “Inland marshes” (class 4.1.1) and “Salt marshes” (class 4.2.1) in high nature value farmlands were also incorporated.

The final layer has a 100 m resolution and the value of each pixel corresponds to the share of land identified as semi-natural grasslands (ranging from 0/16 to 16/16).

2.5 Elaboration of input data for the landscape mosaic and connectivity analyses

To run the models and produce the indicators described in the following section 4, the above-described layers were combined and integrated through a stepwise approach to obtain improved layers for four main land cover categories:

- Artificial areas, including urban fabric, roads and other artificial infrastructures
- Woody vegetation, including forests *strictu sensu* and any form of non-forest woody vegetation (tree lines, riparian vegetation, islets, thickets etc.)
- Semi-natural non-forest, including semi-natural grasslands as described in section 2.4, and CLC classes such as moors and heathland, sclerophyllous vegetation, marshes, peats and bogs and also not vegetated areas such as bare rocks or glaciers.
- Agricultural area, including all CLC classes belonging to level 2.

This means that in case of conflicting information, the road layer is considered more accurate than the forest layers which in turn is considered more accurate than the semi-natural grassland layer. The refined CLC is used as last resource in case of absence of more detailed data. Based on these assumptions, the set of decision rules described in the following is applied. The aim is to obtain four different layers at 100 m resolution for each of the five main land covers considered, each representing the abundance of that land cover in a 1 ha cell.

Firstly, the road layer is overlaid with the forest HRL to obtain an improved forest HRL, which is a 25 m resolution binary layer of presence/absence of forest (that is: whenever a road pixel overlaps a forest pixel, that cell is corrected to non-forest). By aggregating the original Road layer (25 m) to 100 m resolution, the share of road pixels in 100 m cell is derived (Road share layer).

The next step is to consider the herbaceous SNV abundance layer. For each cell in which the abundance of roads + forest is < 100%, the value of the herbaceous SNV layer is added. If the resulting value is > 100%, the value of the semi-natural grassland share is corrected (lowered) so that the final sum is 100%. If, after summing the semi-natural grassland share, the value is still < 100%, the refined CLC map is used to determine to which land cover category the remaining of the cell area is assigned. Two different rules are applied depending on whether the CLC class for that cell is forest or not (as for forest land cover class the corrected HRL forest layer is considered to be more accurate than CLC).

Table 1 shows the correspondence between the layers described in sections 2.1 - 2.4, the CLC classes and the four main land cover categories considered in this study (plus water bodies).
The layers described in section 3.1-3.4 are processed hierarchically in this order:

1. Road Layer (resolution: 25 m)
2. Forest High Resolution Layer (resolution: 25 m)
3. Semi-natural grassland in agricultural land (resolution: 100 m)
4. Refined Corine Land Cover (resolution: 100 m)

This means that in case of conflicting information, the road layer is considered more accurate than the forest layers which in turn is considered more accurate than the semi-natural grassland layer. The refined CLC is used as last resource in case of absence of more detailed data. Based on these assumptions, the set of decision rules described in the following is applied. The aim is to obtain four different layers at 100 m resolution for each of the five main land covers considered, each representing the abundance of that land cover in a 1 ha cell.

Table 1. Lookup table defining the four main land cover categories (plus water bodies) from CLC classes and other used layers.

CLC ID	Refined CLC class (resolution 100 m)	Other Layers	Main Land cover category
111	Built-up High Density	Road layer from Open Street Map 25 m resolution	Artificial
112	Built-up Medium Density		
113	Built-up Low Density		
2	Discontinuous urban fabric		
3	Industrial or commercial units		
4	Road and rail networks and associated land		
5	Port areas		
6	Airports		
7	Mineral extraction sites		
8	Dump sites		
9	Construction sites		
10	Green urban areas		
11	Sport and leisure facilities		
12	Non-irrigated arable land		Agriculture
13	Permanently irrigated land		
14	Rice fields		
15	Vineyards		
16	Fruit trees and berry plantations		
17	Olive groves		
18	Pastures		
19	Annual crops associated with permanent crops		
20	Complex cultivation patterns		
21	Land principally occupied by agriculture, with significant areas of natural vegetation		
22	Agro-forestry areas		
23	Broad-leaved forest	Copernicus Forest High Resolution Layer 25 m resolution	Woody vegetation and forests = Forest
24	Coniferous forest		
25	Mixed forest		
26	Natural grasslands	Semi-natural Grassland share 100 m resolution (0-16)	Natural and semi-natural non-forest = non-Forest
27	Moors and heathland		
28	Sclerophyllous vegetation		
29	Transitional woodland-shrub		
30	Beaches, dunes, sands		
31	Bare rocks		
32	Sparsely vegetated areas		
33	Burnt areas		
34	Glaciers and perpetual snow		
35	Inland marshes		
36	Peat bogs		
37	Salt marshes		
38	Salines		
39	Intertidal flats		
40	Water courses		Water
41	Water bodies		
42	Coastal lagoons		
43	Estuaries		
44	Sea and ocean		

Firstly, the road layer is overlaid with the forest HRL to obtain an improved forest HRL, which is a 25 m resolution binary layer of presence/absence of forest (that is: whenever a road pixel overlaps a forest pixel, that cell is corrected to non-forest). By aggregating the original Road layer (25 m) to 100 m resolution, the share of road pixels in 100 m cell is derived (**Road share layer**).

The next step is to consider the herbaceous SNV abundance layer. For each cell in which the abundance of roads + forest is < 100%, the value of the herbaceous SNV layer is added. If the resulting value is > 100%, the value of the semi-natural grassland share is corrected (lowered) so that the final sum is 100%. If, after summing the semi-natural grassland share, the value is still < 100%, the refined CLC map is used to determine to which land cover category the remaining of the cell area is assigned. Two different rules are applied depending on whether the CLC class for that cell is forest or not (as for forest land cover class the corrected HRL forest layer is considered to be more accurate than CLC).

If the CLC class it is not forest, the main category to which that class belongs (see Table 1) is assigned to the rest of the cell share. If the CLC class is forest, than the following decision rules are applied: if the cell is inside a forest **core** (as defined by the GUIDOS morphological pattern module), the remaining share is considered "natural and semi-natural non-forest" (non-Forest) - i.e. grassland, moorland, heathland etc. Otherwise, the surrounding CLC classes are examined, and the most common class found in the surrounding cells is assigned to the rest of the cell share.

The following paragraphs illustrate the proposed methodology in different cases.

2.5.1 Case 1

Let's consider a 100 m cell from CLC classified as "agriculture" and the 16 overlapping 25 m cells of the road layer and HRL Forest, plus the value representing the abundance of semi-natural grassland.

Input datasets.

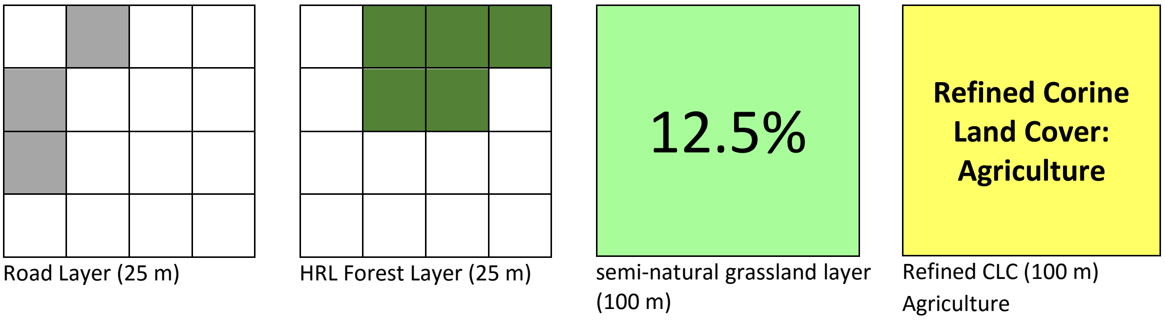
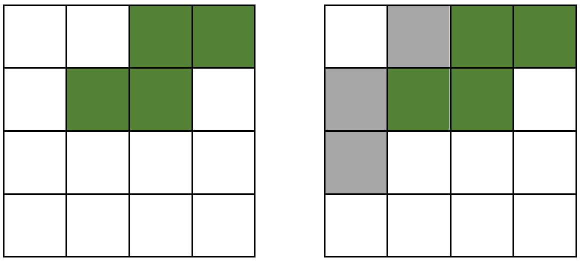


Figure 1. Layers processed to determine the final share of the four main land cover categories on a 1 ha cell: case 1.

The dominant land use in the cell, according to CLC, is agriculture. However, more detailed information from the other input datasets is available, indicating that actually Forest, roads and semi-natural grasslands are also present in the cell.

From the original datasets, the share of Road is 3/16 (18.75%); the share of forest is 5/16 (31.25%); the share of semi-natural grassland is 12.5%. First, the road and HRL Forest are overlapped. In this case, one 25 m cell is considered both as road and forest, thus according to the defined hierarchy, the Forest layer is corrected:



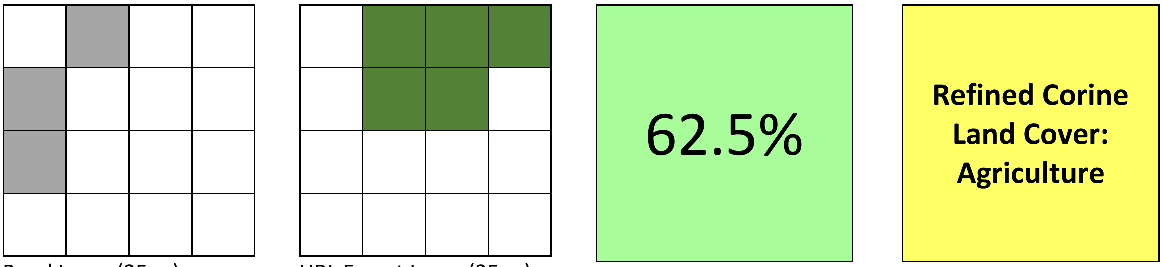
Corrected HRL Forest (25 m) Roads and Forest (25 m)

Figure 2. Corrected Roads and forest shares in 1 ha cell after processing in case 1.

After this operation, the resulting shares of covers are the following: Road: 18.75%; Forest: 25%; semi-natural grassland: 12.5%. Partial total (Roads + Forest + Grassland) = 56.25%. The remaining of the share (100-56.25) = 43.75% is considered agricultural land.

2.5.2 Case 2

Input datasets are the same as case 1 except that the semi-natural grassland abundance is 62.5%.



Road Layer (25 m) HRL Forest Layer (25 m) semi-natural grassland layer (100 m) Refined CLC (100 m): Agriculture

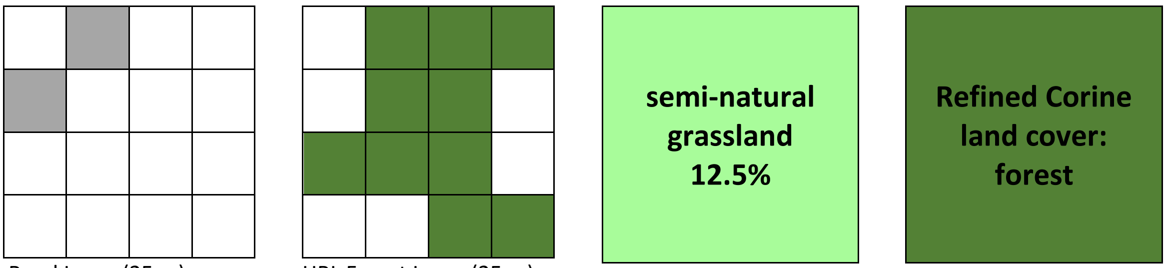
Figure 3. Layers processed to determine the final share of the four main land cover categories on a 1 ha cell: case 2.

After correcting the Forest layer, the share of Roads and forest is 7/16 = 43.75%. By summing it up with the semi-natural grassland share, the resulted share would be >100%. The semi-natural grasslands value is thus corrected so that the total adds up to 100%. The final shares are therefore:

Artificial: 18.75%; Forest: 25%; non-Forest: 56.25%; Agriculture: 0%

Note that even if semi-natural grassland in agricultural land is present, the CLC class is not necessarily "agriculture" since the "agricultural mask" used by Garcia-Feced et al. (2014) includes also High Natural Value Farmland map (Paracchini et al., 2008) that includes areas (i.e. grazed areas in sclerophyllous vegetation) not necessarily identified as agriculture by CLC.

2.5.3 Case 3



Road Layer (25 m) HRL Forest Layer (25 m) semi-natural grassland layer (100 m) Refined CLC (100 m): Forest

Figure 4. Layers processed to determine the final share of the four main land cover categories on a 1 ha cell: case 3.

In this case, by applying the usual procedure, the share of Artificial, Forest (corrected) and SNV non-forest (represented by semi-natural grasslands) are respectively 12.5%; 56.25%; and 12.5%, the partial total adding up to 81.25%. We don't use directly the Refined CLC land cover category in this case as this would increase the share of forest, thus leading to lose the more detailed information given by the HRL Forest Layer. Instead, we follow the process described above. The forest morphological pattern layer obtained by GUIDOS is used to determine whether the non-forest cells are contained in a *perforation*. These are non-forest (background) cells completely within a forest core according to the MPSA taxonomy (see Figure 5 below and the Morphological Spatial Pattern Analysis Manual in the GUIDOS toolbox for more details)

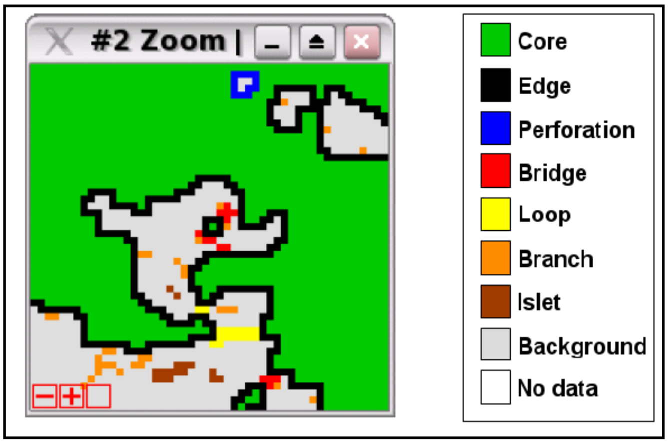


Figure 5. Example of Morphological Spatial Pattern Analysis. Source: GUIDOS software

The number of non-Forest 25 m cells within a perforation are considered semi-natural non-forest, thus the corresponding share value is summed to the semi-natural grassland share (if present), to obtain the final non-Forest share. If they are not within a perforation, the 8 adjacent 100 m CLC cells are considered and the most common found class is identified. The remaining 25 m cells are assigned to that class, and the final shares are calculated accordingly. The non-Forest cells might be urban or non-Forest, so they would be added to the roads and to the semi-natural grassland value to obtain the final "Artificial" and non-Forest share, respectively. If the most common class of the 8 adjacent cell is "Forest", the second most common class is considered. If all the 8 adjacent cells are "Forest", the remaining cells are considered as non-Forest even they are not within perforations.

The diagrams in Figure 6, 7, 11, 13, 14 illustrates the implemented flowcharts and modelled algorithms using the following legend:

	GIS Operation
	Input layer
	Intermediate layer
	Final Layer
	Sub-model

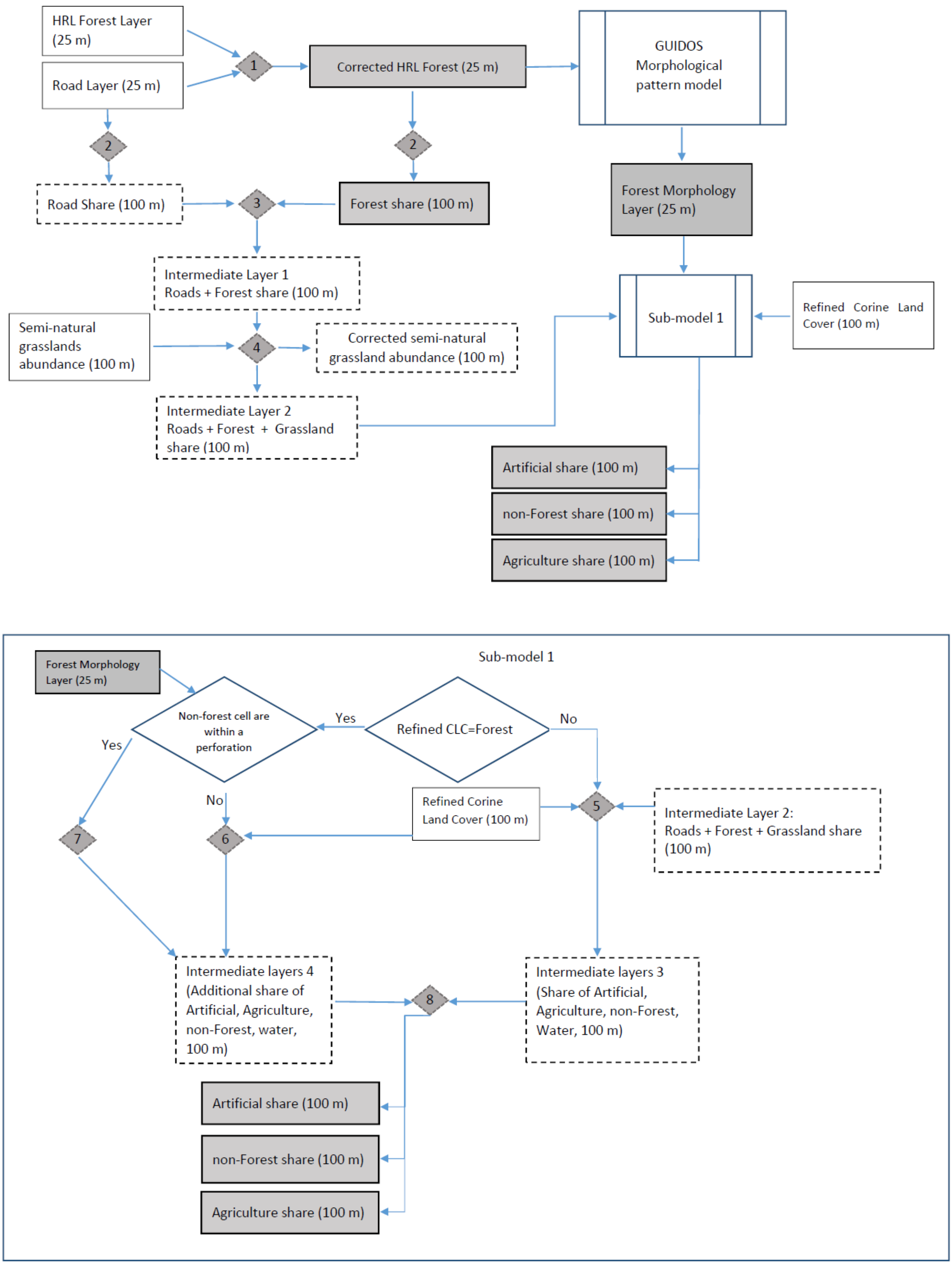


Figure 6. Flowchart of the processing to obtain the layer of abundance of the four main land cover classes

3 Model and core set of indicators

3.1 Core set of indicators

The JRC integrated modelling framework and set of indicators are described in Estreguil et al. 2014a. They were customised to better capture the fine-scale pattern of SNV in the landscape and support the building of a connected GI for Europe; in particular, conceptual and processing amendments were made for (1) characterising the structural continuity of SNV by customising the morphological model, (2) characterising the landscape pattern surroundings of SNV by customising the landscape mosaic model, (3) characterising the functional connectivity of SNV by customising the connectivity model, and amending it with a corridor mapping function, and (4) developing a new cost-benefit assessment approach to guide and prioritise the geolocation of ecosystem improvement actions.

3.2 Customisation of indicators for forest and agriculture

3.2.1 Customisation of the habitat morphology model

In the original morphological model (Estreguil et al., 2014a), the focal class is described according to 17 morphological classes that are further regrouped into 5 classes: *Interior* (or core) areas which are beyond a fixed distance to the border (edge width), *Boundaries* (or *edge*) of interior areas, *Connectors* and *Branches* which are Linear features that are always connected to interior areas, and *Islets* which are small areas with no interior part and which are physically isolated. Indices based on these morphological shapes are the shares of the focal class into *Interior*, *Boundary*, *Connector* and *Branch* (Linear feature) and *Islet*.

Within this study, we decided to characterise the morphological shapes of three focal classes, namely the semi-natural vegetation (SNV), its sub-class forest only (Forest) and its other sub-class the natural and semi-natural non-forested vegetation including grasslands (non-Forest). The land coverage of each focal class was obtained for two cases: (1) when the focal class is abundant enough within one hectare, *i.e.* applying a natural share threshold within one hectare cell of at least 50% vegetated (8/16), and (2) when it is predominant within one hectare, *i.e.* applying a natural share threshold within one hectare cell of at least 85% vegetated (14/16). Within the one hectare cell, the vegetation can be spatially contiguous (structurally continuous) or fragmented. When two adjacent cells are structurally connected (8-connectivity), the vegetation they contain may or may not be adjacent but would always be distant less than a fixed distance. The fixed distance which is an input parameter of the model was set at 100 m which corresponds to the cell edge size. This means that hectares including abundant or predominant vegetation and classified as 'interior' cells will always be beyond 100 m distance to cells with no abundant vegetation or other land uses. Linear features will be elongated with a maximum width of two cells (200 m), islets will be small patches with a maximum size of 4 cells (4 ha) and/or a maximum width of 2 cells (200 m).

The 17 morphological shapes retrieved by the model were resumed into three shapes as *compact* shapes by merging *interior* and *boundaries*, *linear* shapes and *islets*. *Networks* were obtained by merging *compact* and *linear* shapes. The processing flowchart of the habitat morphology model is detailed in Figure 7. The structural continuity of semi-natural vegetation were characterised on the basis of maps of the three morphological shapes (*Compact*, *Linear*, *Islets*) and of their respective shares. We then assumed that structurally connected semi-natural vegetation features, i.e. the *networks*, could be considered as potential GI elements. The maps of *networks* and *islets* were also proposed to identify where to enhance structural continuity (by connecting *islets*). Outcomes of the model also answered if there were any differences in the structural continuity of woodlands when compared to other semi-natural vegetation (like grasslands).

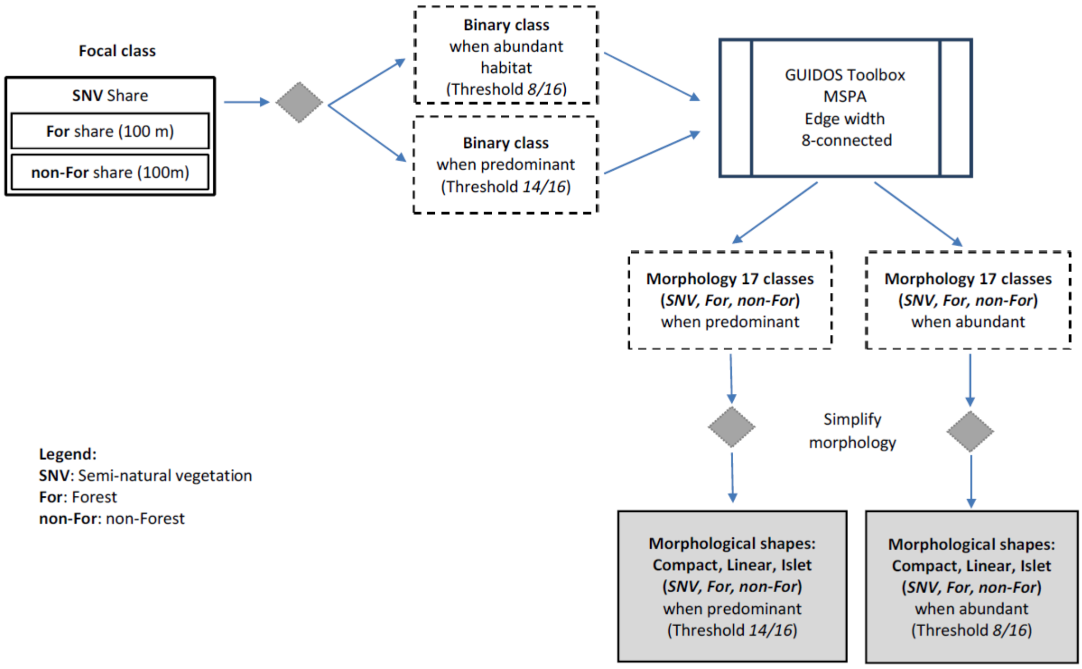


Figure 7. Flowchart of the habitat morphology model.

3.2.2 Customisation of the landscape mosaic model

The user decides upon three land cover types of interest in the landscape (natural: Forest + non-Forest, Agriculture and Artificial) with the aim to describe their mosaic patterns in the landscape. The model enables the discrimination of various mosaic patterns types depending on proportional presence of land cover in the immediate surrounding of each piece of land with thresholds applied for each of the three land cover types. The land cover proportion is performed using a square window of 9x9 pixels, which examines the landscape up to about 500 m in the neighbourhood around each cell.

3.2.2.1 Mosaic pattern for natural vegetation in forest lands

On the basis of the original version of the mosaic triangle presented in Estreguil et al. (2014a), the landscape is resumed into 4 main mosaic pattern categories principally related on natural land proportion (Table 2 and Figure 8). Successively, the mosaic pattern is extracted for forest cover (Figure 9), obtaining three mosaic pattern categories as follows:

- Forest in 'core natural' patterns (NN) are areas where forest are always adjacent to natural/semi-natural habitats or in the interior part of forest patches (agriculture and artificial covers less than 10%).
- Forest in 'mixed natural' patterns (MN) are areas where forest are embedded in a predominant natural context (natural share between 60% and 90%), but are significantly fragmented by agricultural and/or artificial land (total share between 10% and 40%).
- Forest in 'some natural' patterns (SN) are areas where forest are in a predominantly non-natural context with a natural share always below 60% (i.e. forest patch in predominant agricultural landscape).

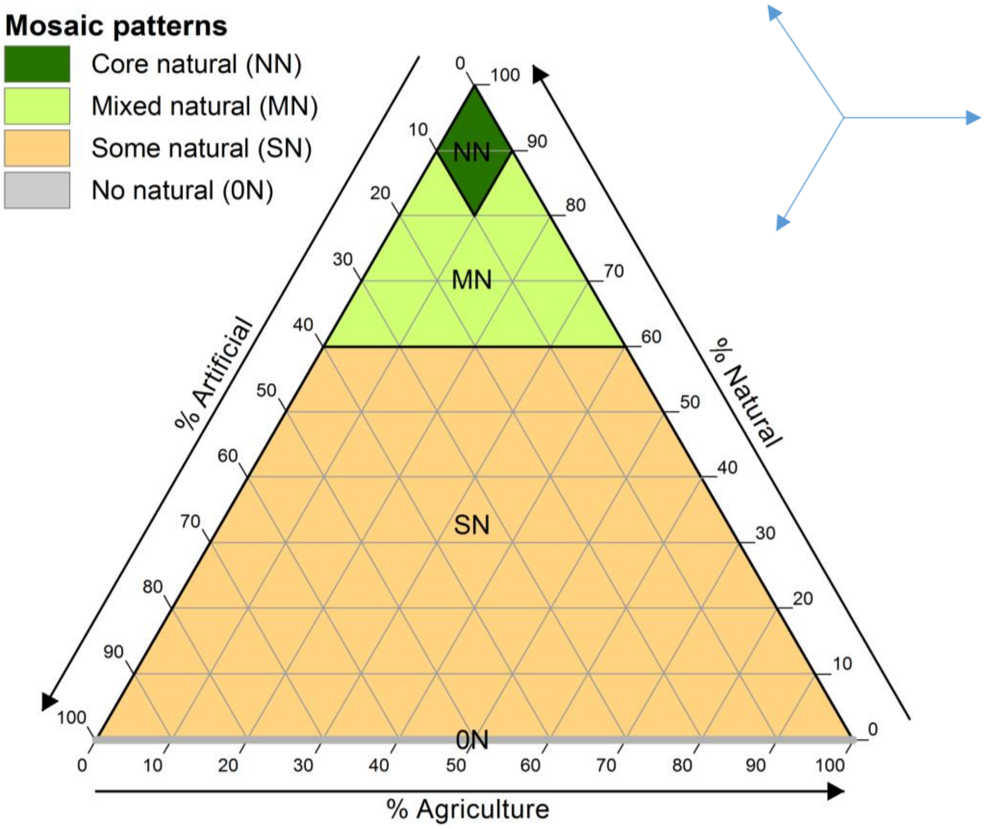


Figure 8. Mosaic pattern triangle model and thresholds of different landscape mosaic types.

Table 2. Identified thresholds of mosaic patterns of natural lands.

NUMB.	DESCRIPTION	NATURAL	AGRICULTURE	ARTIFICIAL
1	**Core Natural (NN)**: natural with low presence of artificial areas	]80-100]	[0-10[	[0-10[
2	**Mixed Natural (MN)**: Natural with medium presence of artificial lands	[60-90[	[0-40[	[0-40[
3	**Some Natural (SN)**: Natural with high presence of artificial lands	]0-60[	[0-100[	[0-100[
4	**No Natural (0N)**	0	[0-100]	[0-100]

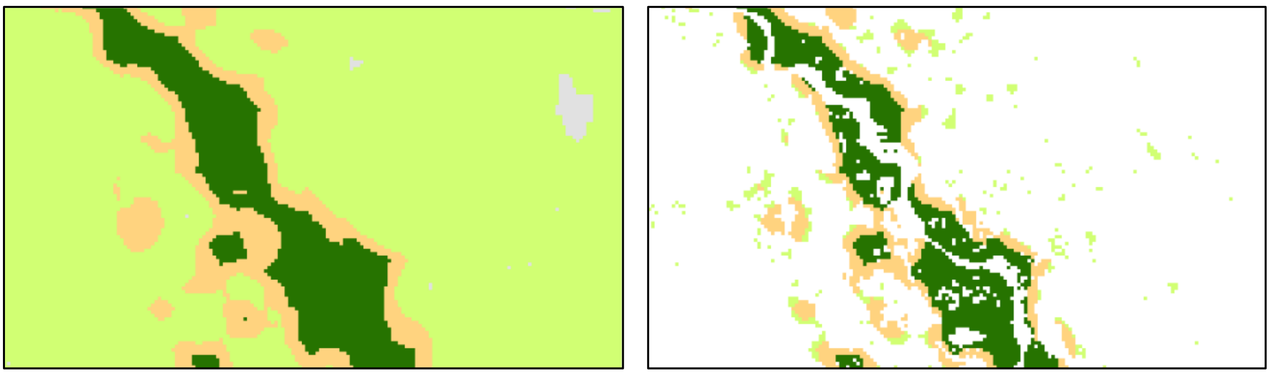


Figure 9. Four landscape patterns as result of the mosaic process (on the left) and the same landscape patterns extracted for the forest cover, representing the focal class (on the right).

3.2.2.2 Mosaic pattern for natural vegetation in agricultural lands

The original version of the mosaic triangle was amended in order to capture more details, particularly when areas of SNV occupy less than half of the landscape and are distributed as small or elongated patches, like in agricultural lands. A new triangle (Figure 10) and thresholds (Table 3) were proposed to describe the mosaic patterns of agricultural lands.

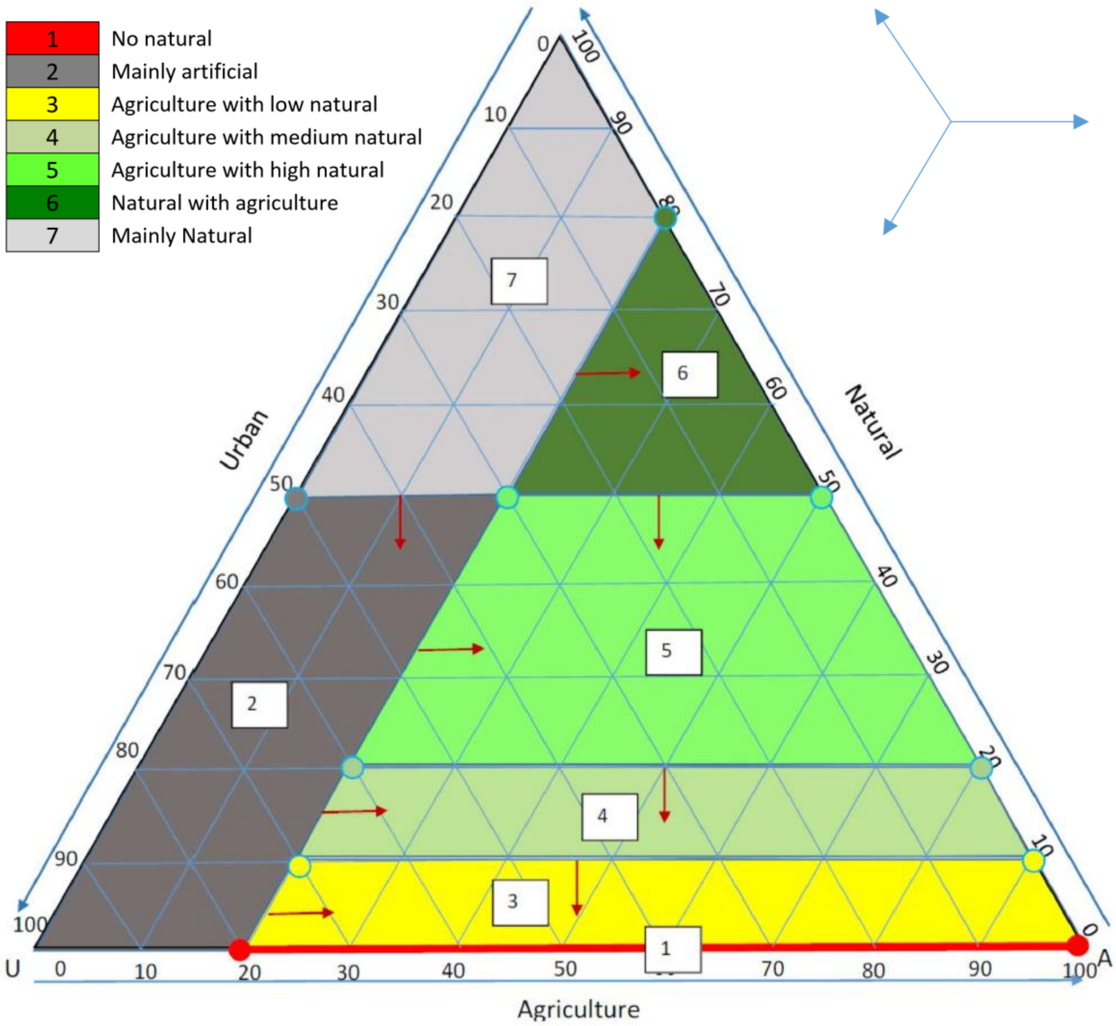


Figure 10. Customised mosaic pattern triangle model and thresholds of different landscape mosaic types.

Table 3. Identified thresholds of the mosaic patterns of agricultural lands.

NUMB.	DESCRIPTION	Agriculture	Natural	Artificial
1	No natural	[20-100]	0	[0-80]
2	Mainly artificial	[0-20[	[0-50]	]30-100]
3	Agriculture with low natural	[20-100[	]0-10]	[0-80]
4	Agriculture with medium natural	[20-90]	]10-20]	[0-70[
5	Agriculture with high natural	[20-80]	]20-50]	[0-60[
6	Natural with agriculture	[20-50[	]50-80]	[0-30[
7	Mainly Natural	[0-20[	]80-100]	[0-50[

As previously done for the morphology, we decided to characterise the mosaic pattern in the surroundings of three focal habitat classes, namely the SNV, the Forest only and the non-Forest only. With the data at hand, this was done for two cases: (1) when the focal class is abundant enough within one hectare, *i.e.* applying a natural share threshold within one hectare cell of at least 50% vegetated (8/16), and (2) as soon as the focal class is present within one hectare, *i.e.* applying a natural share threshold within one hectare cell of at least one pixel vegetated (1/16). The shares of each three land cover types (natural, urban/artificial, agricultural) within one hectare were used as input data. The size of surroundings was set to a window of 9x9 cells, *i.e.* 810,000 m^2 circa 1 km^2.

The two versions of the mosaic model triangle were applied; this resulted in 7 mosaic pattern types for the triangle well suited for agricultural lands (Figure 10), and resulted in 4 pattern types for the one more suitable for predominantly natural landscapes (Figure 8). The processing flowchart is illustrated in Figure 11. The outcomes of the model were the map of landscape mosaic types defined according to each triangle, and the maps for each focal class when present and/or abundant. The shares of the landscape mosaic types were calculated for each focal class.

The two mosaic pattern models aim at answering what are the typical, most dominant and most frequent mosaic patterns in a geographical region of interest. By combining them with the morphological shapes of the semi-natural vegetation, the landscape surroundings of *islets* and of *networks* as potential GI elements can be characterised. The same can be done when considering only *islets* and *networks* of woodlands or of semi-natural non forest vegetation.

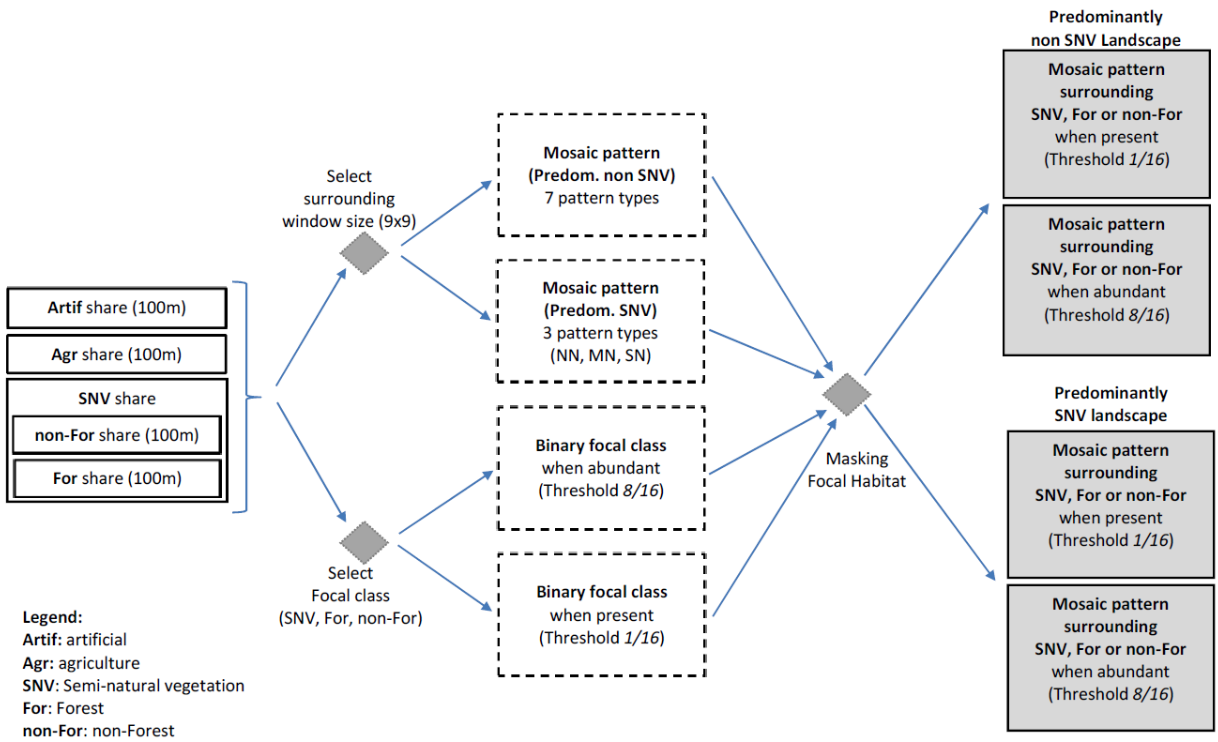


Figure 11. Flowchart of the landscape mosaic pattern model

3.2.3 Customisation of the connectivity model: corridor mapping and cost-benefit function

The original version of the functional connectivity model is built upon a network based habitat availability model and a probabilistic model of connectivity that is based on the size and topology of SNV and the effective distances between habitat patches for a given species dispersal ability. The computation is obtained from the Conefor[3] free open source software (Saura and Torné, 2009). The effective distance depends on the average dispersal capability of selected species in the landscape. The land cover/land uses make the landscape more or less hostile, resistant/costly or favourable for the dispersal of the species. The "least-cost path" method provides the cheapest cost path from habitat to habitat patches through the landscape matrix. The cost distance matching the 50% probability corresponds to the given average dispersal distance of the species multiplied by a given average landscape cost per distance unit. The probability of dispersal in the landscape then decreases as an exponential function of the effective distance. Functional habitats are defined as those which are connected by at least one least-cost path. Functionally isolated habitats are those from which no least-cost paths are found. For a geographical area of interest, two functional connectivity indices – the habitat area weighted Root Probability of Connectivity (RPC) and the Root un-weighted Average Probability of Connectivity (RAPC) – are computed from the simplified power weighted probability of dispersal function introduced in Estreguil et al. (2014a).

For the current study, the connectivity analysis was conducted to support building a GI for Europe, by first creating a land cover resistance layer based on potential GI and non GI landscape elements, and second by assessing the connectivity of potential GI components at regional scale (macro-connectivity) and at more local scale (micro-connectivity). The final aim was to identify connectivity gaps and propose best cost-effective solutions for connectivity enhancement at both scales. The macro-connectivity analysis identifies corridors of best dispersal that reflect needs of terrestrial 'connective sensitive' species of medium dispersal capability (500 m in agriculture up to 5,000 m in natural areas) but are likely to also benefit a large range of species. The micro-connectivity analysis addresses more the needs of species of low dispersal capability like pollinators or flying biological control agents (200 m up to 500 m).

3.2.3.1 Micro-connectivity and cost-benefit analysis

We conducted a micro-connectivity analysis on the study area highlighted in Figure 12. We were interested to assess the potential of agricultural areas in contributing to biodiversity maintenance and to the supply of ecosystem services provided by mobile-agents with lower dispersal capabilities as wild bees for pollination or flying biological control agents (like certain species of ladybugs, dragonflies or wasps) for pest control. A micro-connectivity analysis at a more local scale was conducted by focussing on identifying if and where, connectivity in agricultural land with low shares of SNV, could be improved by increasing the SNV share.

The definition of "habitat" cells was based on studies from literature estimating the amount of uncultivated area in agriculture-dominated landscapes necessary to support a minimum of biodiversity and ecosystem services such as pollination and pest control (e.g. Banaszak, 1992; Kretschmer and Hoffmann, 1997). Estimates vary but recent studies indicate that a 20% of semi-natural non crop habitat appears to be the threshold above which biodiversity can be conserved and pollination and biological control provided (Tscharntke et al., 2011).

Studies also indicate that the effect of the share of SNV in agricultural landscapes on biodiversity and ecosystem services is not linear, but is more pronounced in simple landscapes (with < 20% of SNV)

[3] www.conefor.org

that in complex ones. This is to say that after a certain threshold, the marginal benefit of adding new SNV decreases.

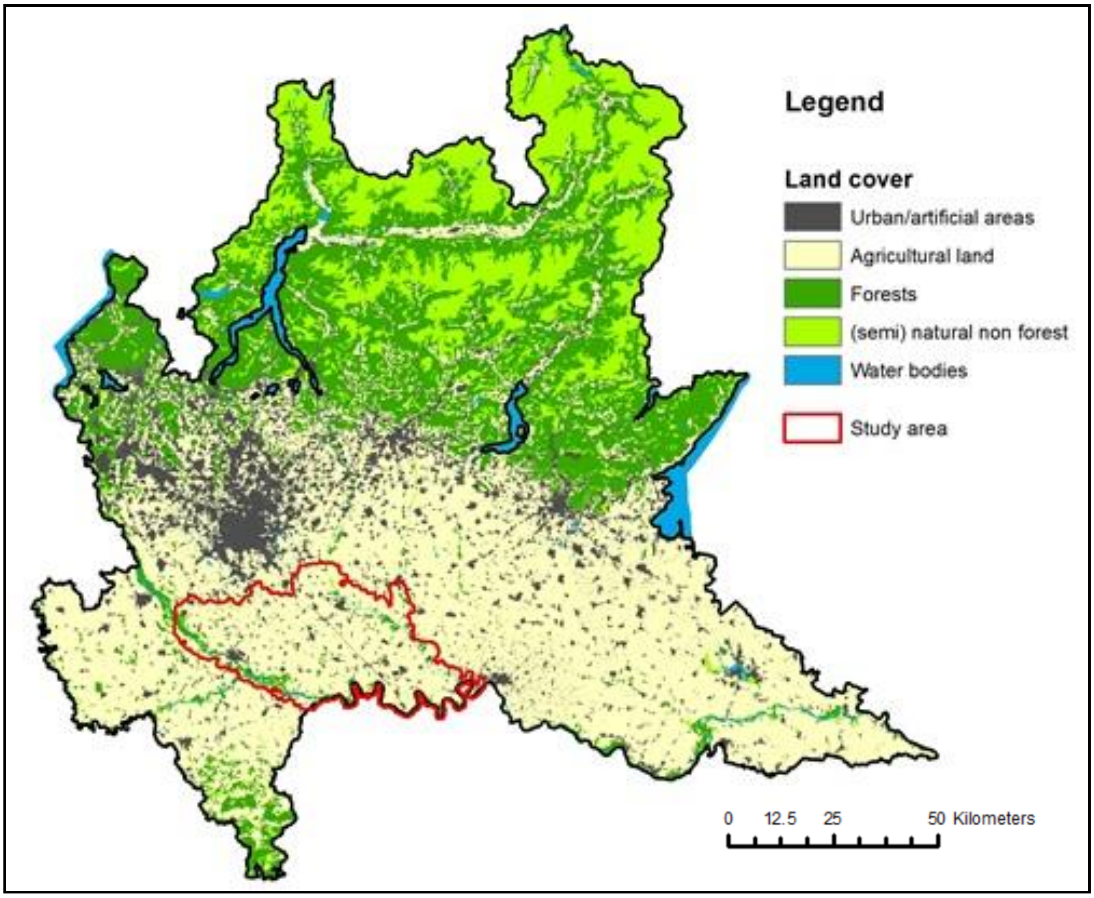


Figure 12. Land cover map of Lombardy and study area for the micro-connectivity.

We considered as habitats those 100 m cells where the sum of woody and non-woody SNV is close to or greater than 20% (3 pixels of 25x25 m on 16 total pixels in each 100x100m cell is equal to 18.75%). To determine the probability of connection between two separate nodes, we used the dispersal range of European wild bees and other pollinators from literature (Greenleaf et al., 2007, and references therein). This study reports, for three mining bees species common in Europe, the typical and maximum foraging distances, defined as the distances within which cumulatively 50% and 90% of individuals are observed to fly and return to the nest. In absence of data on their relative importance for pollination we averaged these values across the species and defined a decaying function of dispersal probability of 50% at 200 m and 10% at 540 m, considered respectively as the typical and maximum dispersal distance (i.e. nodes at distance greater than 540 m were considered not connected). We assumed that such distances are representative also of flying ranges of beneficial pest predators. Since we considered flying organisms, we did not assign different costs of dispersal to different land covers in this second exercise, the landscape resistance was considered neutral.

Subsequently, we assigned a cost of conversion to habitat to each non-habitat cell, defined as the loss of revenues from agricultural production a farmer would incur if he/she decided to have 20% of the land uncultivated and covered by semi-natural vegetation. Therefore, the cost C for each cell j is given by:

$$C_j = \left(0.2 - SNV_j\right) \times MGVA_j \qquad (1)$$

Where:

- SNVj is the current share of semi-natural vegetation in the *j*th cell ($0 \leq SNV_j < 0.2$)
- $MGVA_j$ is the agricultural gross margin including premiums under CAP Pillar I (€/ha) taken from the CAPRI model (Britz and Witzke, 2012) and available at the spatial resolution of the Homogeneous Spatial Mapping Units (1 km^2)

This intended to simulate the actual implementation of agri-environmental measures as defined by EC regulation 1305/2013, whereby the amount of payments to farmer is determined so to cover additional costs and income foregone resulting from the commitments undertaken. For this exercise, we neglected fixed additional costs (which can be considered constant in the study area, as this is relatively small and homogeneous from an agricultural point of view) and considered the agricultural gross margin as a proxy of income foregone. Only agricultural cell with less than 20% of SNV where considered eligible, whilst urban areas, roads and water bodies were excluded.

We first defined the current network, made up by all cells where SNV share greater or equal to 3/16, then we calculated the increase of connectivity in different scenarios, by simulating the conversion of selected cells from "non-habitat" to habitat and associated a cost to each scenario, so as to compare the cost-effectiveness of different policy strategies.

Secondly, we hypothesized to convert those cells with a share of SNV already close to the "habitat" thresholds, i.e. those with a current share of 2/16. This represents a "minimum effort" scenario, in which we suppose that, in absence of any other policy measure, only farmers for which the loss of productive land is minimized will renounce to it in favour of SNV.

At the opposite side of the policy space, we defined a fully-connected scenario, where all points of the study area can be reached by flying organisms with the defined dispersal ranges with a certain probability, propagating from already existing nodes. To identify the additional nodes in this scenario (non-habitat cells to be converted to habitat), we implemented a semi-automatic procedure, due to the high number of potential new nodes (see section 5.3.2).

3.2.3.2 Macro-connectivity and cost-benefit analysis

We were interested to characterise the macro-connectivity of potential GI *networks* of SNV for the whole region, including the identification of main corridors of dispersal for 'connectivity sensitive' species and main barriers due to the most hostile landscape for these species.

At regional scale, a new land use/cover cost (resistance) map was created using the landscape characterisation defined in European Environment Agency (2014) into beneficial (as a proxy of GI components) and deleterious (as a proxy non- GI components) lands to nature (favourable to hosting habitats and species, including their dispersal). We considered that the SNV are more likely to benefit a large range of species. Hostile land uses for the dispersal of animals and plants between natural habitats are based on the threats and disturbances they often represent for biodiversity, such as land uses derived from urbanisation, road infrastructure and to a less extent, intensive agriculture. The resistance values were assigned to every cell and they refer to the cost of movement inside them (square of 1 ha) per distance unit (1 m). The costs range from a minimum of 1 (100% of SNV share within the cell) to a maximum of 100 (100% of artificial surfaces) with continuing values (floating numbers) proportional to the 16^{th} share of the 3 land cover classes, assuming that the resistance is 1 for SNV lands, is 10 for agricultural lands, and is 100 for artificial surfaces (urban, national roads, highways and motorways).

Table 4. Cost factor per land cover and corresponding distances reached at 50% probability and 1% of probability of dispersal (maximum dispersal distance) when the land cover is homogeneously distributed; values are related to species with intermediate dispersal capacity (macro-connectivity analysis).

Land class	Cost factor per map unit	Distance at 50% prob.	Distance at 1% of prob. (Max dispersal)
Natural and semi-natural (SNV)	1	5 km	~33 km
Agriculture	10	500 m	~3 km
Artificial	100	50 m	~330 m

To avoid heavy computation and time constraints over large regions, we conducted the connectivity analysis at macro-scale, typically well suited for terrestrial species with intermediate dispersal capacity like mammals such as 5 km on average in natural lands. The idea was to identify main networks of SNV, made of cells predominantly vegetated, quantify their connectivity at regional level and then map the most functional connectivity paths between *networks* as well as main corridors of feasible dispersal and identify bottlenecks. The processing flowchart of the macro-connectivity analysis is presented in Figure 14. The pattern of SNV in the landscape was simplified by selecting only those hectares of land where vegetation was predominant *i.e*. above 85% (natural shares of SNV of at least 14/16 within cells), by computing the morphological analysis and retaining only *networks* of SNV (thus excluding *islets*) and by regrouping them into clusters when they were apart less than one kilometre distance (those 100x100 m) cells were considered connected regardless the landscape matrix resistance in between them. Least-cost paths between clusters were calculated and two connectivity indices – RAPC and RPC – were computed on the basis of the clusters areas, the cost factors per map unit and resistance classes, the distances values for a 50% probability of dispersal. The maximum dispersal distance (cost limit for distant clusters beyond which habitats are not considered connected) was set when the dispersal probability is 1% of, which corresponds to a distance of circa 33 km in a homogeneous SNV cover (Table 4). A subset of the "most possible" least-cost paths between clusters were selected on the basis of a given threshold of probability of dispersal and the connectivity analysis computed with Conefor software, which is able to identify among all combinations of paths, the ones effectively used in the network. Then corridors of dispersal between clusters were mapped.

Least-cost connected clusters were then grouped into macro-clusters and analysed as single nodes of a regional macro-network, for identifying isolated clusters, sub-networks and the least-cost paths which may potentially connect them. For each of these potential path, having dispersal probability lower than 1%, the amount of needed SNV along the path (expressed in 1/16 of hectare) was then calculated to reduce the environmental resistance up to obtain the minimum dispersal probability of 1%. Using again CAPRI data on agricultural gross margin including premiums under CAP Pillar I, as a proxy for the monetary conversion cost of agriculture to SNV areas, a cost/benefit index per potential paths was computed.

The cost/benefit index (c/b) is given by:

$$c/b = (N_{SNV} * Cavg) / (dPC * AL) \qquad (2)$$

Where:

- N_{SNV} = number of 1/16 ha of SNV needed to reduce the resistant up to 1% of dispersal probability
- Cavg = average monetary cost of conversion of 1/16 ha of agriculture to SNV, computed along the potential least-cost path

- dPC = least-cost path importance computer as difference in Probability of Connectivity index computed with Conefor software
- AL = area of the Region

The index dPC, which evaluates the importance of each least-cost path, was computed with Conefor software with a difference between the Probability of Connectivity (PC) index of a full-connected network and the PC index of the same network without a least-cost path.

The macro-connectivity analysis aims at answering the following research questions: is the region well connected for 'connectivity sensitive' terrestrial species like the ones dispersing 500 m in landscape of intermediate resistance up to a maximum of 5,000 m in natural lands? In particular, where are the main macro-clusters, made of closely spaced SNV? Are corridors of dispersal available between these main macro-clusters? Where the connectivity could be easily enhanced? Where are the most isolated clusters and where would be the best ones in terms of their monetary cost in comparison to their benefit to consider for enhancing connectivity? How this macro-connectivity analysis could support the building of a GI at regional level?

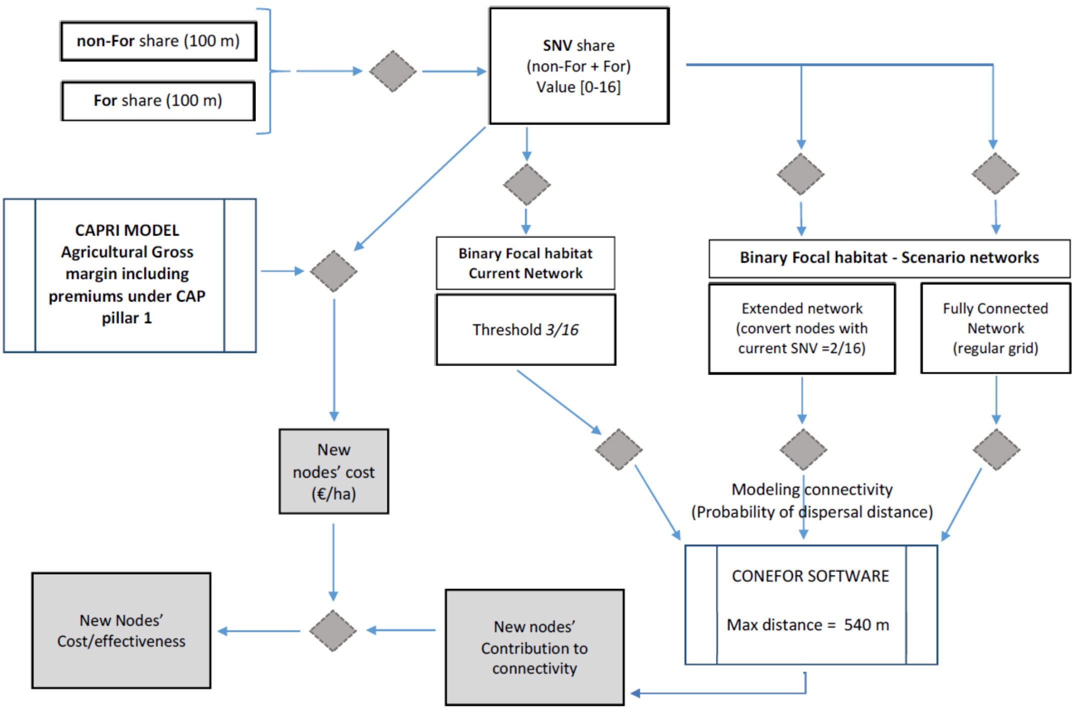


Figure 13. Processing flowchart for the micro-connectivity analysis.

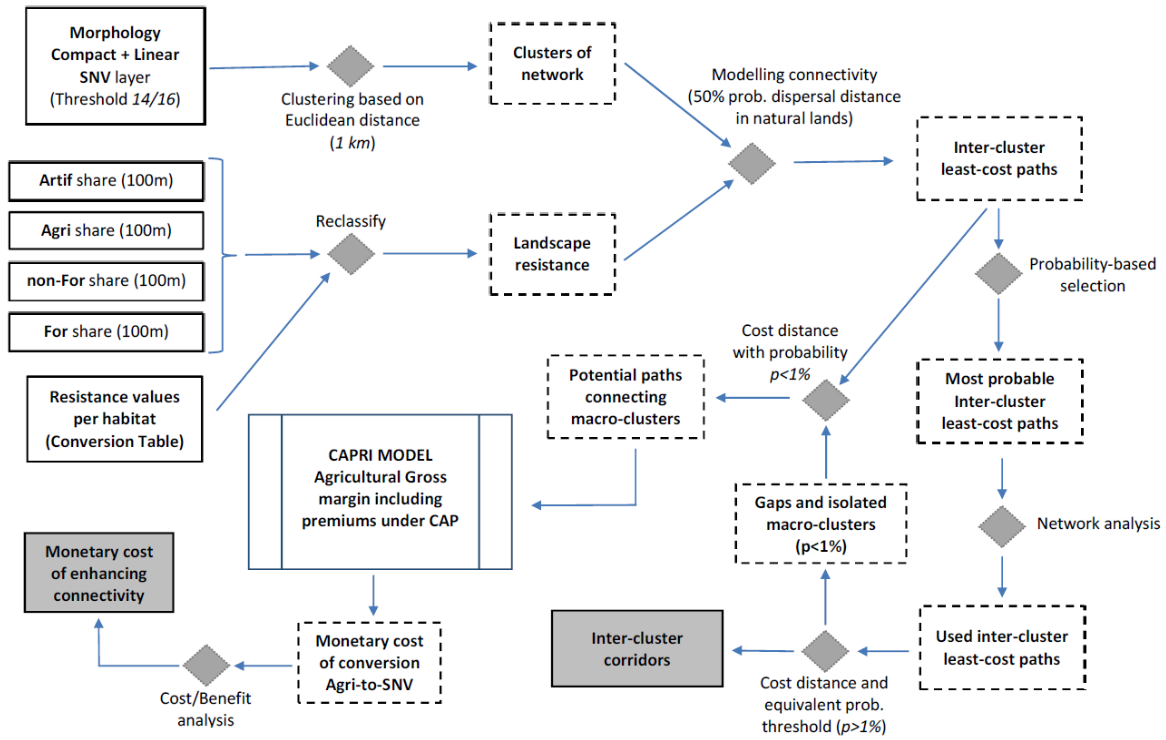


Figure 14. Processing flowchart for the macro-connectivity analysis.

4 Results

4.1 Morphological shapes

The morphological analysis was applied to each cell with SNV, to cells with only Forest and to cells with only non-Forest, according to two thresholds of vegetation abundance in one hectare of land: abundant vegetation 8-16 (more than 50% of cover), predominantly vegetated 14-16 (more than 85% of cover). The three morphological shapes – *linear* and *compact* features, *islets* – were mapped for SNV, for Forest and non-Forest vegetation. Figure 15 illustrates the map of a possible GI made of cells with predominantly vegetated cells (SNV14-16). The map shows that semi-natural lands are predominant, with a compact shape and well connected in the northern and western part of the region corresponding to the western Alps and their foothills while they are more fragmented in the Po Plain. In the Po plain, natural riparian vegetation is noticeable with their linear shapes along the Po River and affluent. Also, we can see many *islets* of vegetation sparsely distributed and embedded in the agricultural landscape. The charts in Figure 16 provide the shares of the three morphological shapes for each focal class.

In Lombardy, cells with abundant vegetation (SNV8-16) represented approximately 25% of the Region. This proportion was reduced to 21% when solely considering predominantly vegetated cells (SNV14-16). In both cases, SNV was composed of approximately 60% of woodlands and 40% of other semi-natural vegetation. The structural continuity of SNV resulted relatively high with 95% distributed as potential GI *networks* and its pattern rather compact (less than 10% of SNV were distributed as *linear* features). We noticed than predominantly vegetated cells tended to be less linear (share of 9% for SNV8-16 and 5% for SNV14-16). The remaining 5% of SNV was fragmented and distributed as *Islets*, representing circa 1% of Lombardy for a total of circa 15,000 cells with an average size in between 3 and 4 ha.

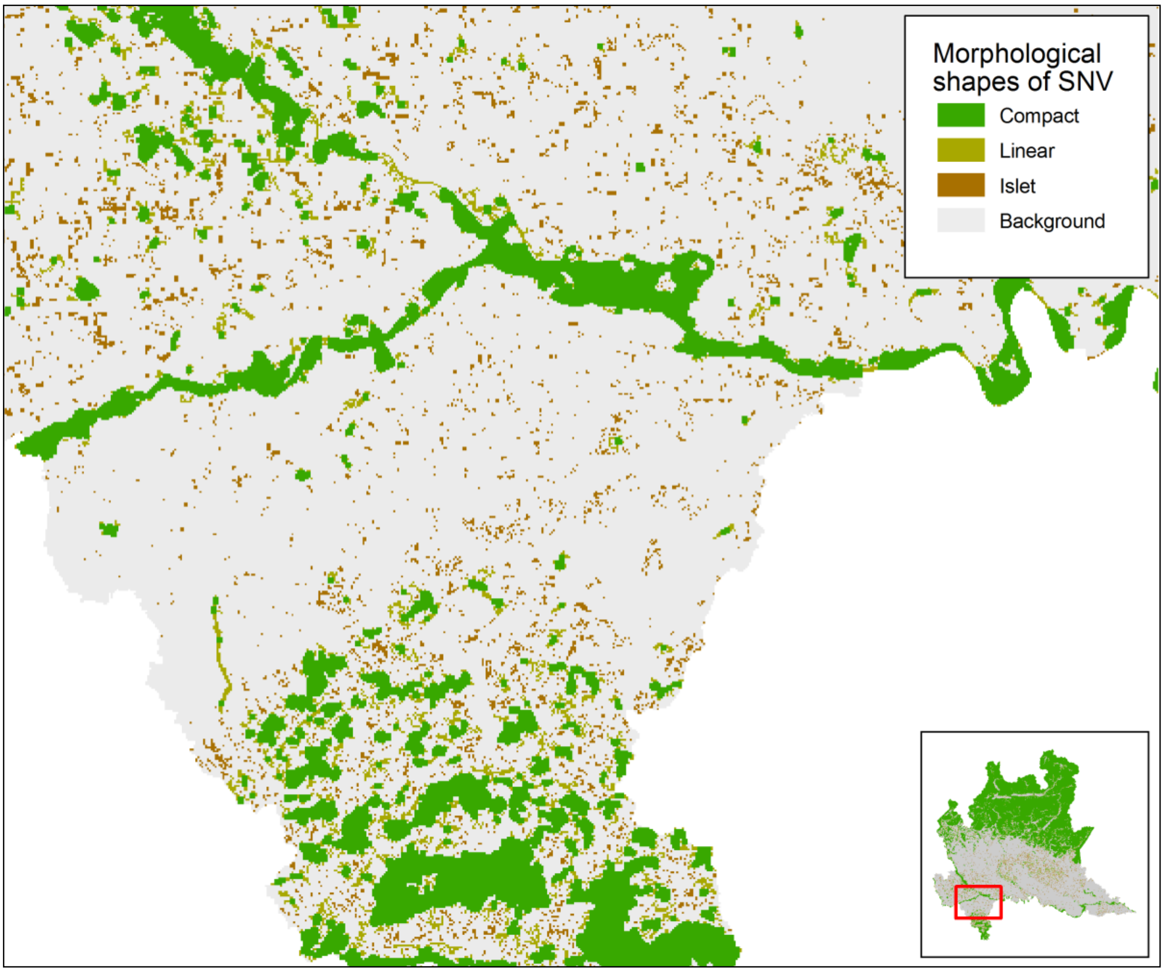


Figure 15. Morphological shapes of hectares of land with abundant semi-natural vegetation (SNV) in Lombardy. Networks are made of linear features connected to compact patches.

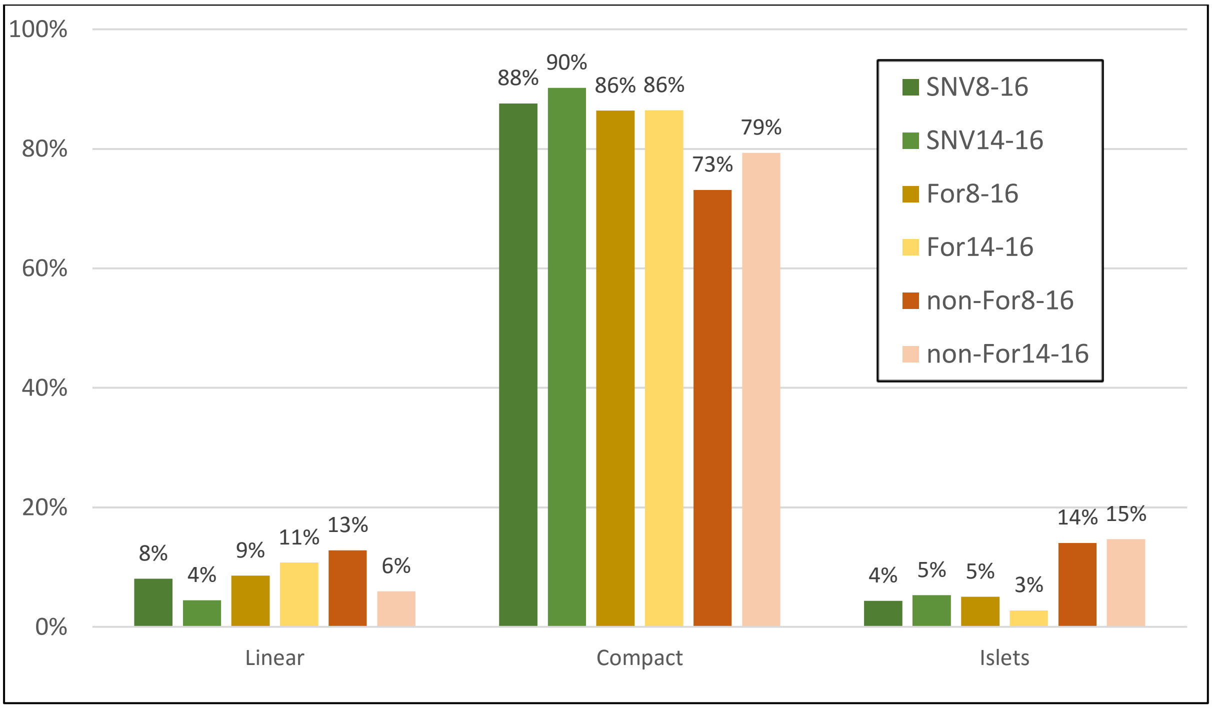


Figure 16. Morphological shapes of hectares of abundant semi-natural vegetated (8-16/16) and predominantly vegetated (14-16/16) lands in Lombardy.

Cells of abundant woody vegetation (For8-16) were similarly connected and compact as the SNV one. Predominantly woody vegetated cells (For14-16) appeared to be even less fragmented and more distributed as linear landscape elements. Semi-natural non-woody vegetation cells (non-For8-16) were found to be less connected and with more linear features (85% distributed as *networks* with 12% as linear features) than the SNV one. Among non-Forest cells, the distribution of only predominantly vegetated ones (non-For14-16) tended to be slightly more compact and less linear. *Islets* of non-Forest were always more numerous than in the case of Forest and represented circa 14% of the total non-Forest with an average size of circa 3.5 ha.

4.2 Landscape mosaic pattern in Lombardy

4.2.1 Landscape mosaic patterns of natural lands

The original version of the mosaic triangle was applied over Lombardy. From the pie chart in Figure 17, we can see that agricultural landscapes with no natural vegetation covered 16% of the region; it was mixed with natural lands for 14% ('Some Natural, mainly agriculture'). 'Core natural' landscapes covered 36% of the region. Predominantly natural landscapes mixed with some agriculture or urban lands represented only 11% of the region. Urban landscapes with no natural vegetation represented 3% of the region; it was mixed with some natural lands for 2% of the region. Landscapes with no predominant land cover but including natural lands represented 18% of the region.

Figure 18 shows that in Lombardy, circa half of cells with abundant SNV were embedded in 'Some Natural' landscape meaning that the kilometre square surroundings these cells was predominantly agricultural or/and artificial and included less than 60% of natural lands. More than one third of the cells were in a 'Core Natural' landscape and distributed as contiguous kilometre squares (SNV above 80%). We then analysed separately woody (For) and non-forest vegetation (non-For). The distribution of forested cells (For1-16 (not shown), For8-16 and For14-16) appeared to be predominantly in a 'Core Natural' landscape. 90% and even more of cells with woody vegetation (both For8-16 and For14-16) had their surroundings with semi-natural lands (SNV) share above 60%. This was less pronounced in the case of non woody vegetation (non-For1-16 (not shown) similar to non-For8-16). Circa 25% of the non-For cells were in 'Some Natural' surroundings, likely in predominant agricultural lands (Agr) where more than 95% of cells had a natural vegetation share below 60% (Agr8-16 or Agr14-16).

In Figure 19, the map shows the three landscape mosaic patterns ('Core Natural', 'Mixed Natural', 'Some Natural') in the immediate surrounding (1 km^2) of the SNV14-16. Edge interface zones are highlighted for each of the three morphological shapes. Due to the overlay, natural lands with a *compact* shape (green shade) and in a 'core natural' pattern (blue shade) appear in green shade. They correspond to interior part of large *compact* patches in the northern part of the region, and to the interior part of linear patches of vegetation when wide enough along the Po and affluent rivers. Few cells of SNV classified as *islets* are in a 'mixed natural' pattern, which could be seen as a positive sign to become GI components due to a more permeable landscape in their immediate surroundings. However, we can notice that most *islets* and small clusters of vegetation in the Po Plain are in a 'Some natural' landscape, thus embedded within predominantly intensively used agricultural lands. More details on the presence and spatial distribution of vegetation are needed on this specific pattern to link with the intensity of land use in agricultural landscapes.

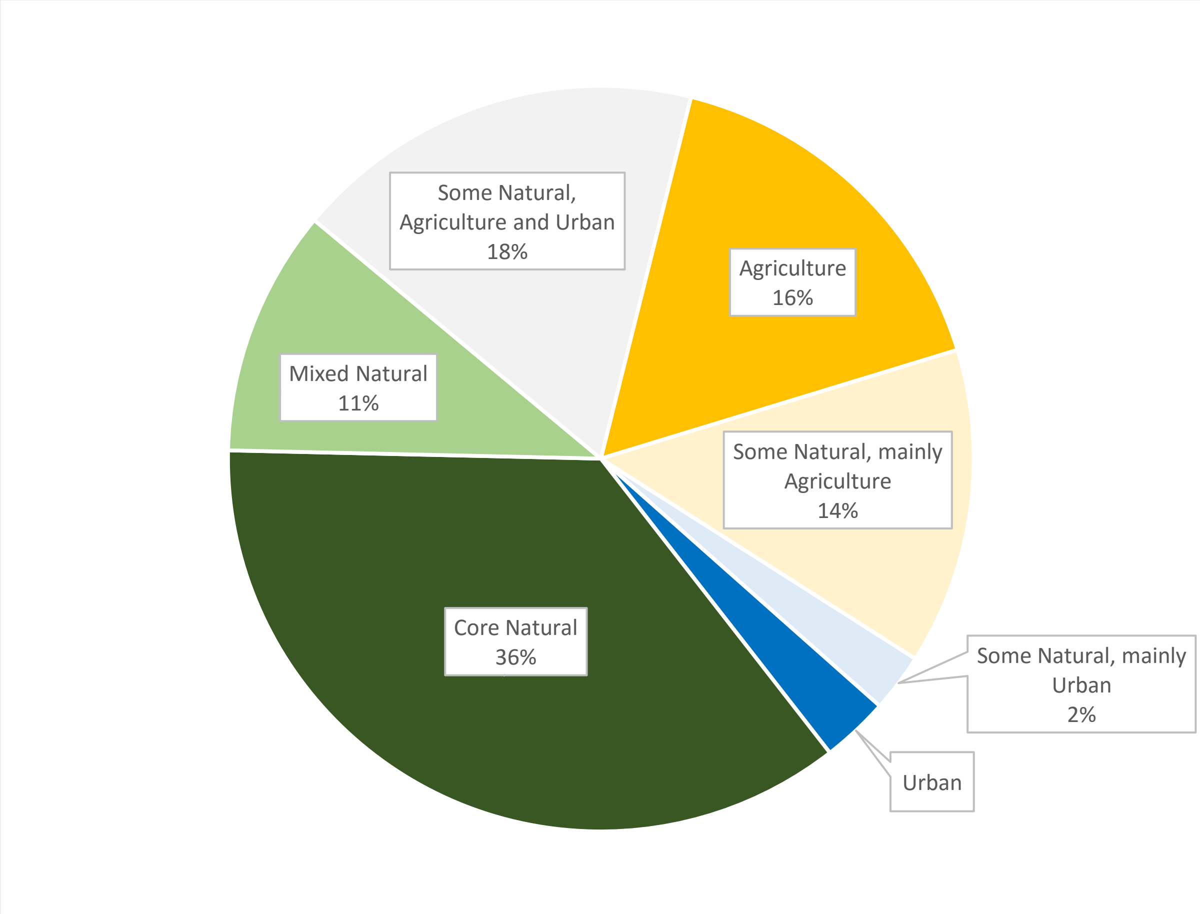


Figure 17. Landscape mosaic pattern types and their shares in Lombardy.

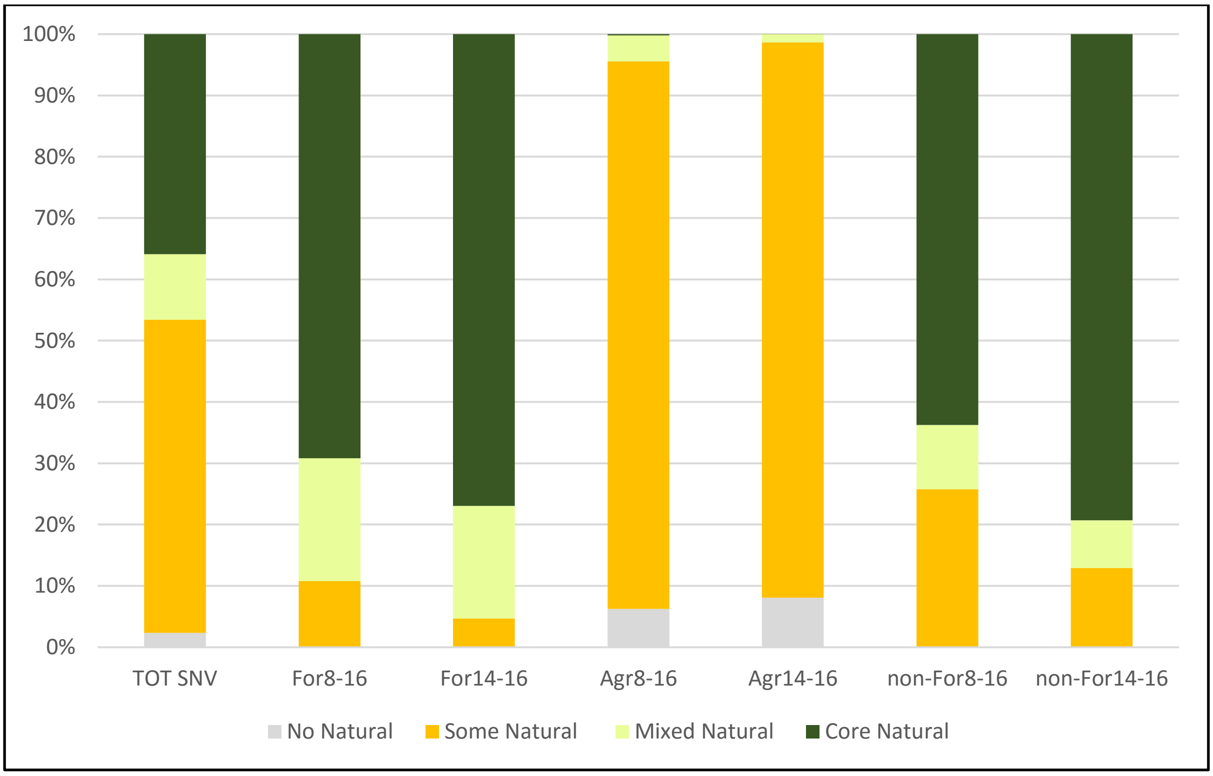


Figure 18. Mosaic patterns of semi-natural vegetation (SNV) in Lombardy, and surroundings patterns of forest (For), agriculture (Agr) and non-forest vegetation (non-For). Share in the hectare cells is abundant (8-16) or predominant (14-16).

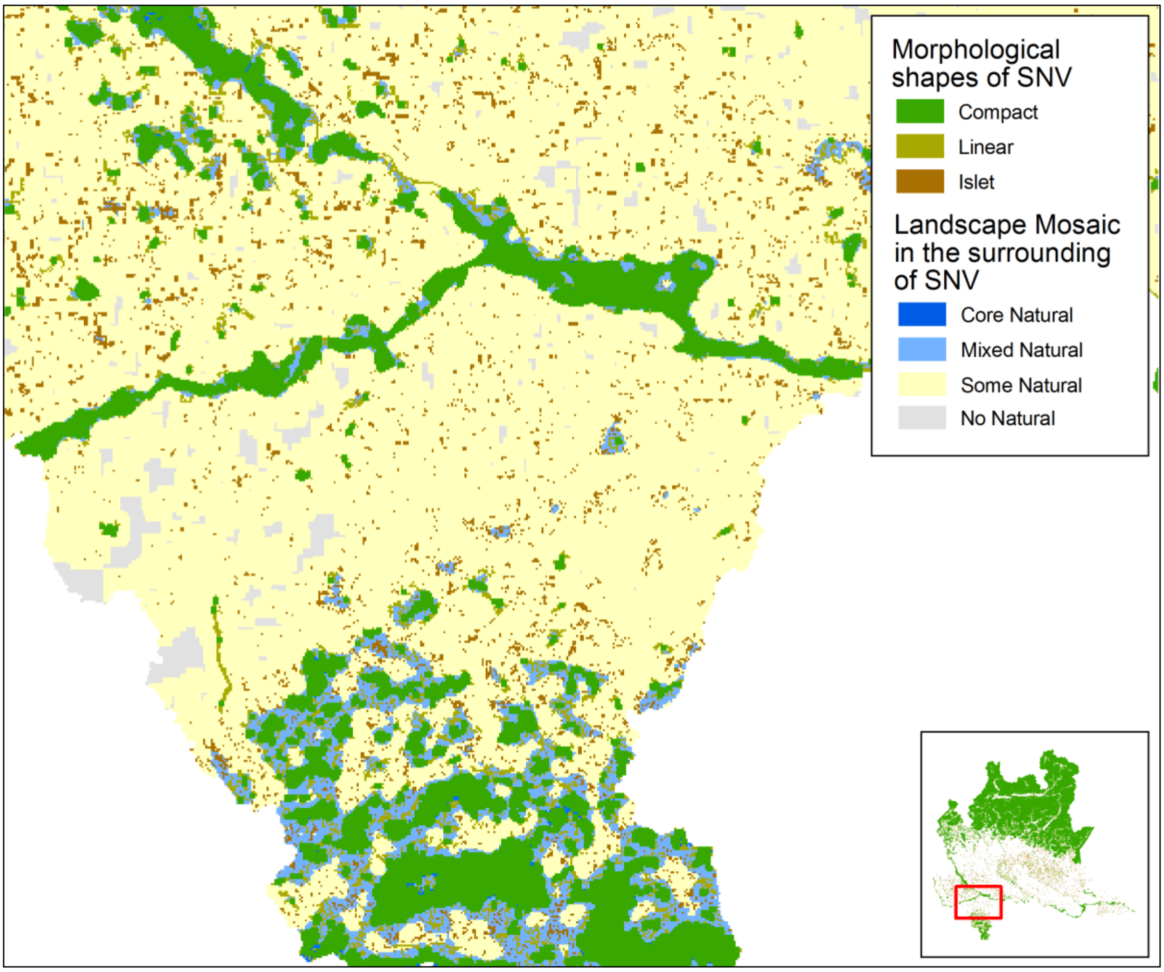


Figure 19. Potential Green infrastructure of semi-natural vegetation (SNV) in Lombardy, its morphology and landscape mosaic pattern in its immediate surroundings.

4.2.2 Landscape mosaic patterns of natural vegetation in agricultural landscapes

Figure 20 shows the shares of the different landscape types according to the customised landscape mosaic model (Figure 10). This was developed to better characterise areas with significant (>20%) presence of agriculture based on the abundance of natural and semi-natural features in the agricultural matrix.

From the pie chart we can see that about 27% of the regional area was made up by agricultural landscapes with relatively low (< 20%) presence of (semi)natural elements. In particular, 9% of the area had some presence of SNV (10-20%), 16% had less than 10% of SNV and 2% was cropland with no semi-natural elements at all. Predominantly natural landscapes accounted for 52% of the regional area, mainly in the northern alpine sector, of 8% was made up by patches of cropped areas or pastures embedded in a natural matrix and 44% by natural areas with no agriculture and some urban areas within it. Predominantly urban landscapes accounted for 6% of the regional area.

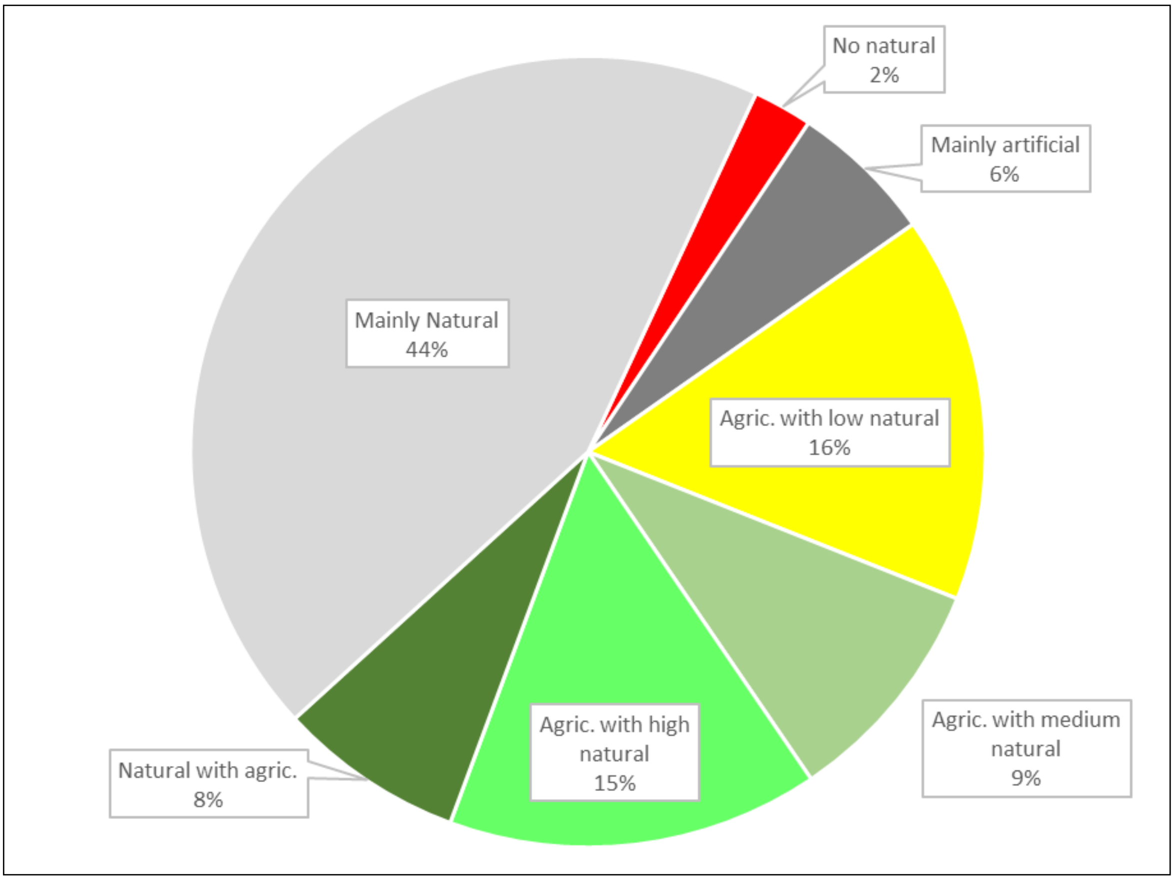


Figure 20. Customised mosaic model land shares of all landscape mosaic pattern types.

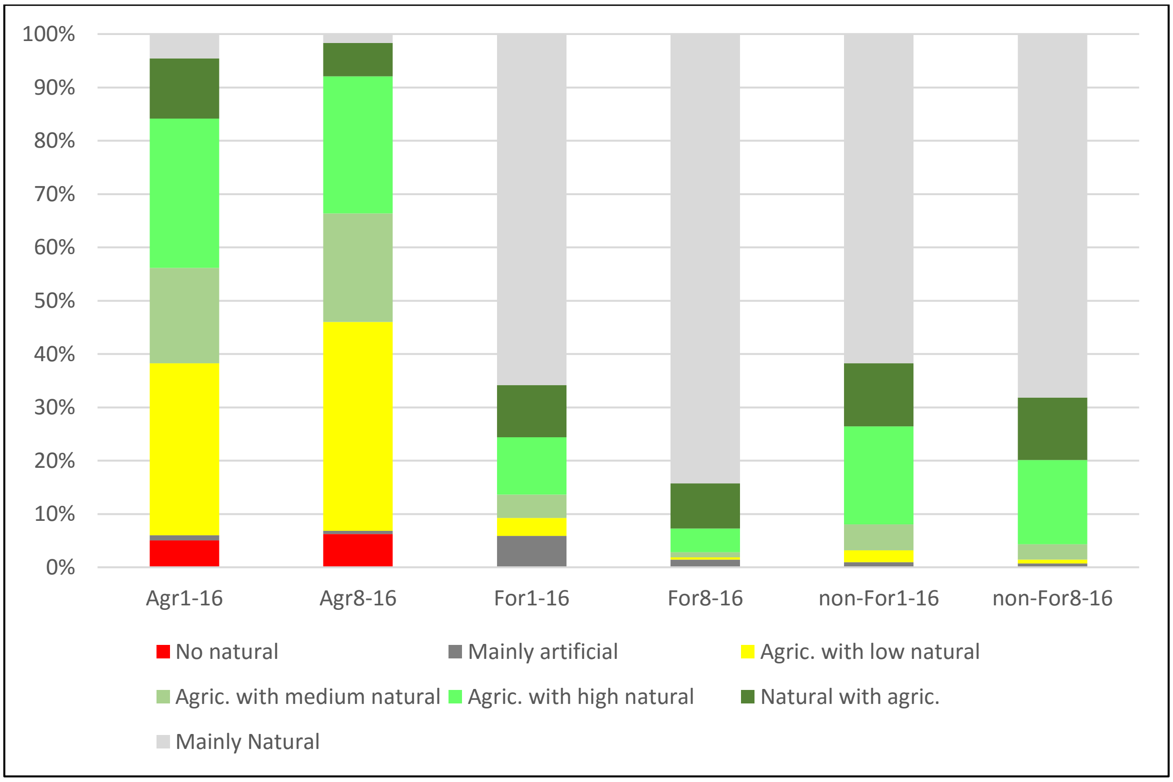


Figure 21. Mosaic patterns in the surroundings of agriculture, forest and non-woody vegetation (respective share in the hectare cells is present (1-16) or abundant (8-16).

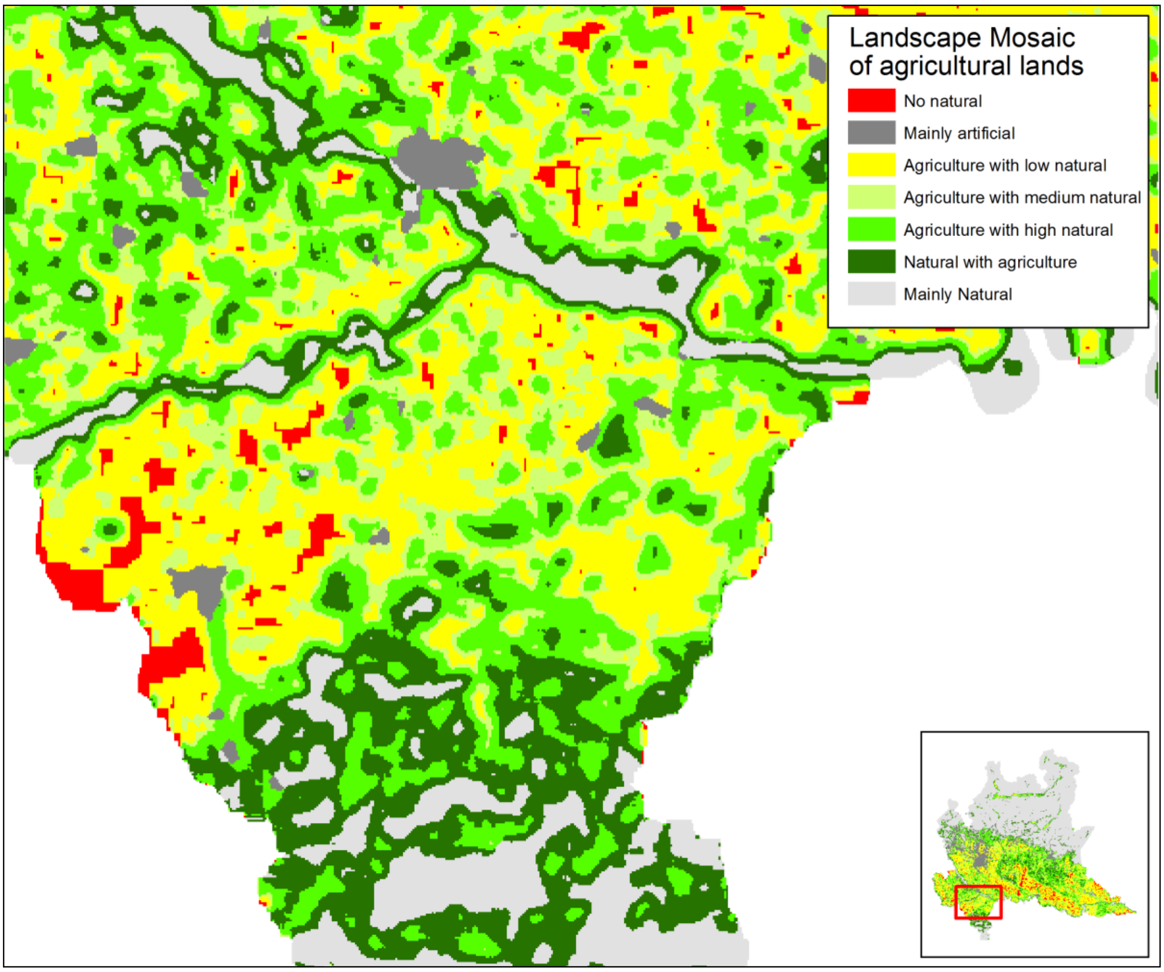


Figure 22. Shares of different mosaic pattern classes in South-west of Lombardy.

4.3 Connectivity of natural/semi-natural vegetation

4.3.1 Micro-connectivity analysis at the sub regional level

The selected study area for the micro-connectivity analysis is a highly intensive cropped area in Southern Lombardy, delimited by three main ecological corridors corresponding to the Ticino and Adda Rivers to the East and West respectively and the Po River to the South. The northern limit corresponds to the administrative boundary of the Province of Milano (NUTS3) and the study area covers the entire Province of Lodi and the share of the Province of Pavia north to the Ticino River, the total area being around 1,690 square km (Figure 12). It is a highly productive agricultural land, with a mix of fodder crops and cereals in the eastern part and prevalence of rice paddies in the western one. It is highly representative of the agrarian landscape of the lower Po plain, which has undergone significant processes of simplification over the last decades and reduction of SNV elements such as tree lines and hedges on field margins.

At the resolution of 100x100 m, the whole study area was made up by 169,000 cells, of which approximately 58,000 classified as habitat and 111,000 as non-habitat (hence potential new nodes). To decrease the number of possibilities, we limited the number of eligible cells by creating a regular grid of (currently) non-habitat 100x100 m cells distant from each other a maximum of 300 m, and excluding cells adjacent to or within 100 m from already existing habitats, as well as cells occupied by artificial areas, as shown in Figure 19.

We selected the minimum number of new nodes allowing the whole study area to be connected, considering the dispersal distances (flying ranges) used in the model. The new network included overall approximately 4,500 nodes, 1,360 original nodes (dark green in Figure 19) plus 3,113 new nodes (light green). This new network was used as input in Conefor to determine the contribution of each new cell to total connectivity. The "node importance" as defined and calculated by Conefor is the decrease in the connectivity metric value caused by the removal of that individual node from the landscape. We had to introduce a further simplification at this stage due again to computational limits: with Conefor, the computation time for estimating the importance of single nodes of a network with *n* nodes is proportional to $(n^2-n)/2$. In this case, the order of magnitude of no. of nodes was 10^3, making the computational times very long.

To overcome this, we selected the number of used links (no. of links from/to each cell multiplied by the times they are used in the computation of the network connectivity), as a proxy for the node importance. In this case, this approximation was considered acceptable because the other node attributes contributing to connectivity, namely area and share of SNV, are constant for each new potential node.

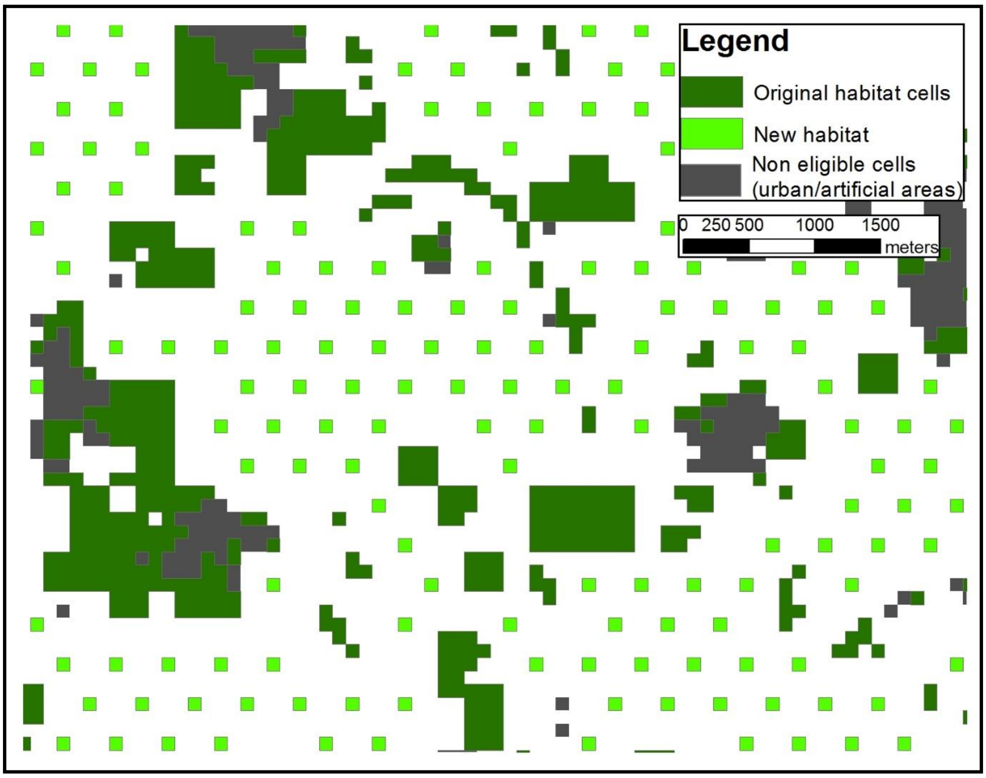


Figure 23. Original habitat network (dark green areas) and simulated new habitats cells (light green).

Finally, we calculated a measure of the cost-effectiveness of conversion of each cell by dividing the cell's importance by the cost *Cj* defined in the equation (1). According to this procedure, new habitat cells could be ranked according to their absolute contribution to the network connectivity and by their cost/effectiveness.

Figure 23 shows the current network in the study area, made up by 1360 nodes. The riparian vegetation along the Ticino, Adda and Po rivers constituted the main network's nodes; a West-East gradient of SNV abundance in the agricultural land in between these nodes could be identified, with decreasing presence of SNV towards the East.

The connectivity of the identified network was calculated with Conefor and used as benchmark. Subsequently, we added to the original network the new nodes corresponding to agricultural cells with a current share of SNV of 2/16. Those were the cells that did not classify as habitats but that had the closest share of SNV to the identified habitat threshold of 3/16. In other words, they were the cells for which conversion to habitat would imply the minimum loss of cultivated land, which might be a relevant policy option while trying to enhance the GI and limiting the loss of agricultural production. The identified cells, shown in red in the Figure 24, covered an area of 439 ha and the total cost of conversion would be 42,982 €/year; the loss of agricultural area would be 27.4 ha.

The increase in connectivity, however, was very limited due to the relatively low number of additional nodes and their spatial configuration as they were mainly adjacent to already existing nodes. Figure 25 shows the scenario in which all the study area was connected by converting to habitat eligible cells according to a regular grid so that habitat cells were distant a maximum of 300 m from each other.

Under this scenario, we simulated a policy pursuing the objective of connecting the whole area with the minimum number of necessary cells regardless of the costs and the loss of agricultural production. Overall, 3,089 new cells (equal to 3,089 ha) would be converted to habitat, with a total expenditure of 1,027,740 €/year and a loss of agricultural area of 576 ha.

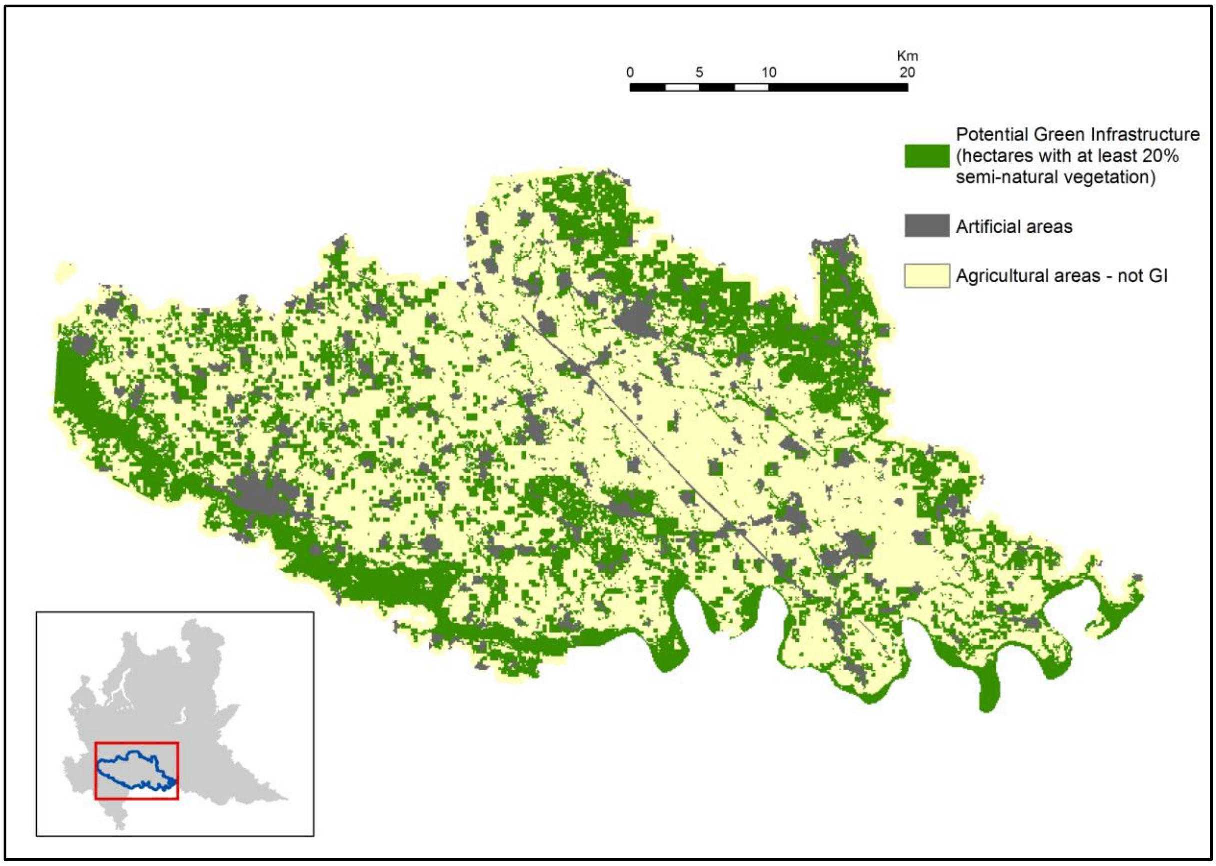


Figure 24. Potential GI elements in the study area.

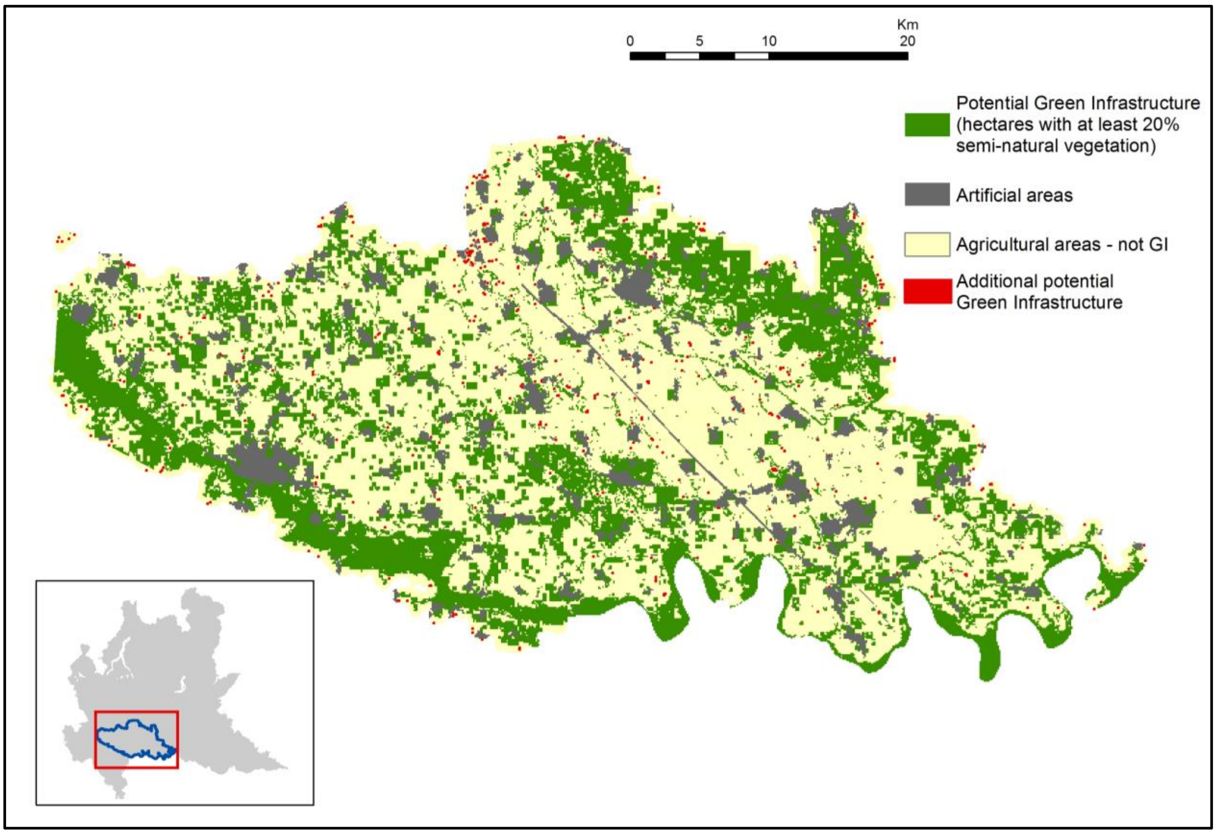


Figure 25. The network with the original nodes (in green) and additional nodes with a current share of semi-natural vegetation = 2/16 (in red).

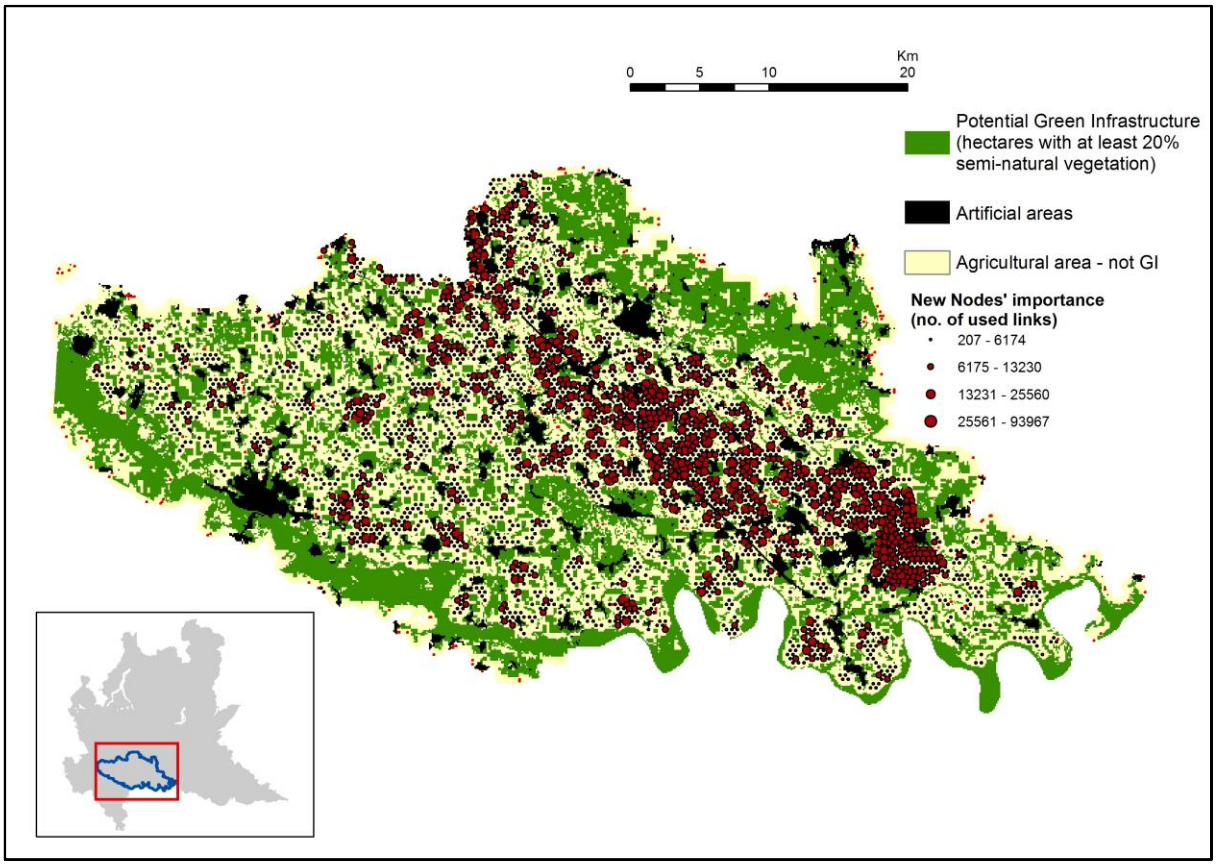


Figure 26. Original network (in green) and new nodes classified according to their importance (no. of used links).

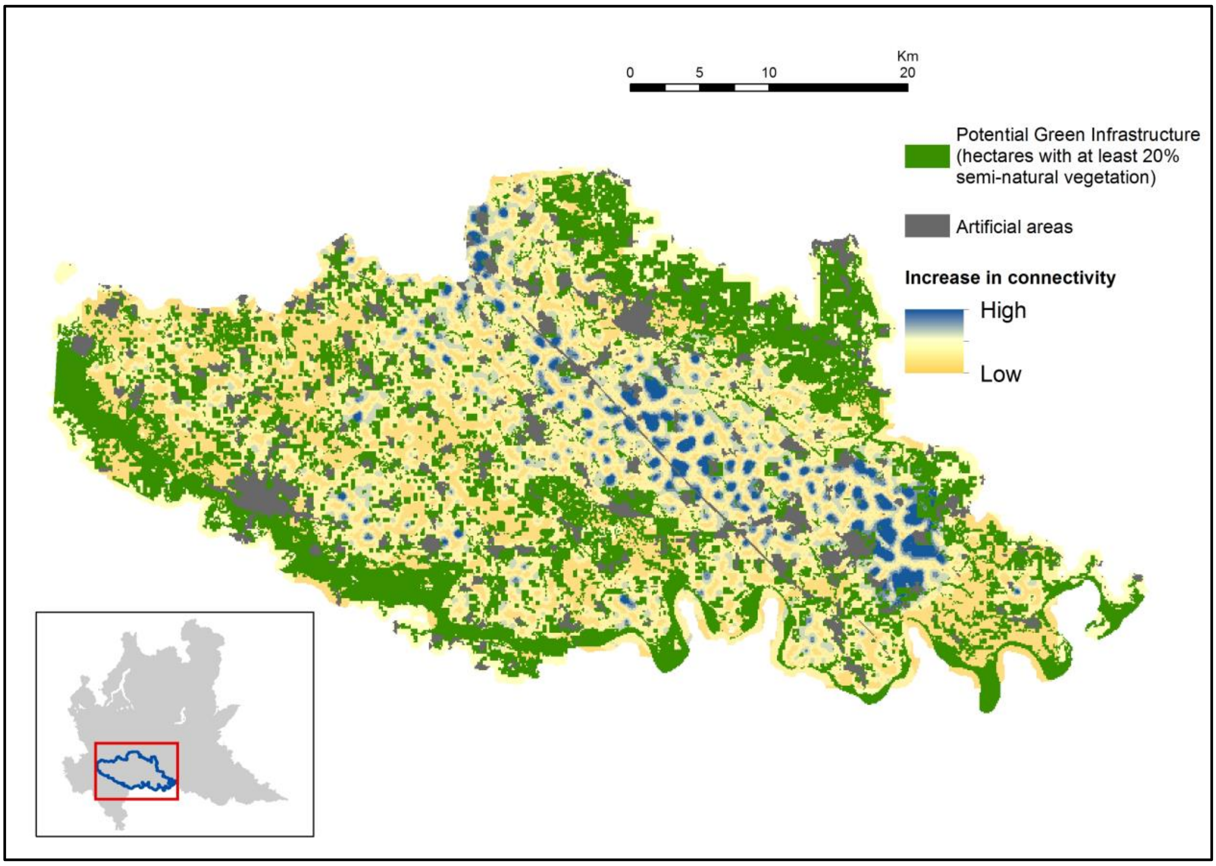


Figure 27. Effect on network's connectivity in case of creation of new habitats node.

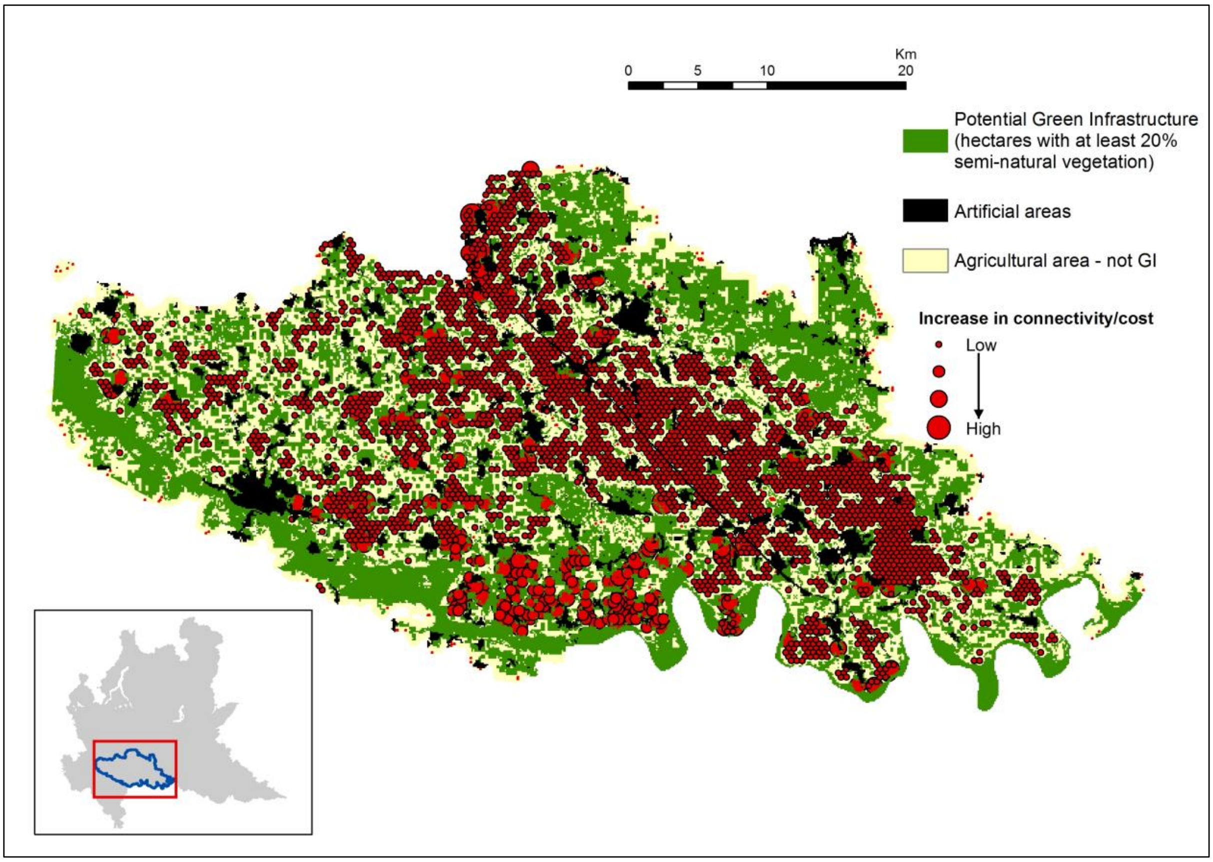


Figure 28. Ratio between node importance for connectivity and cost of conversion.

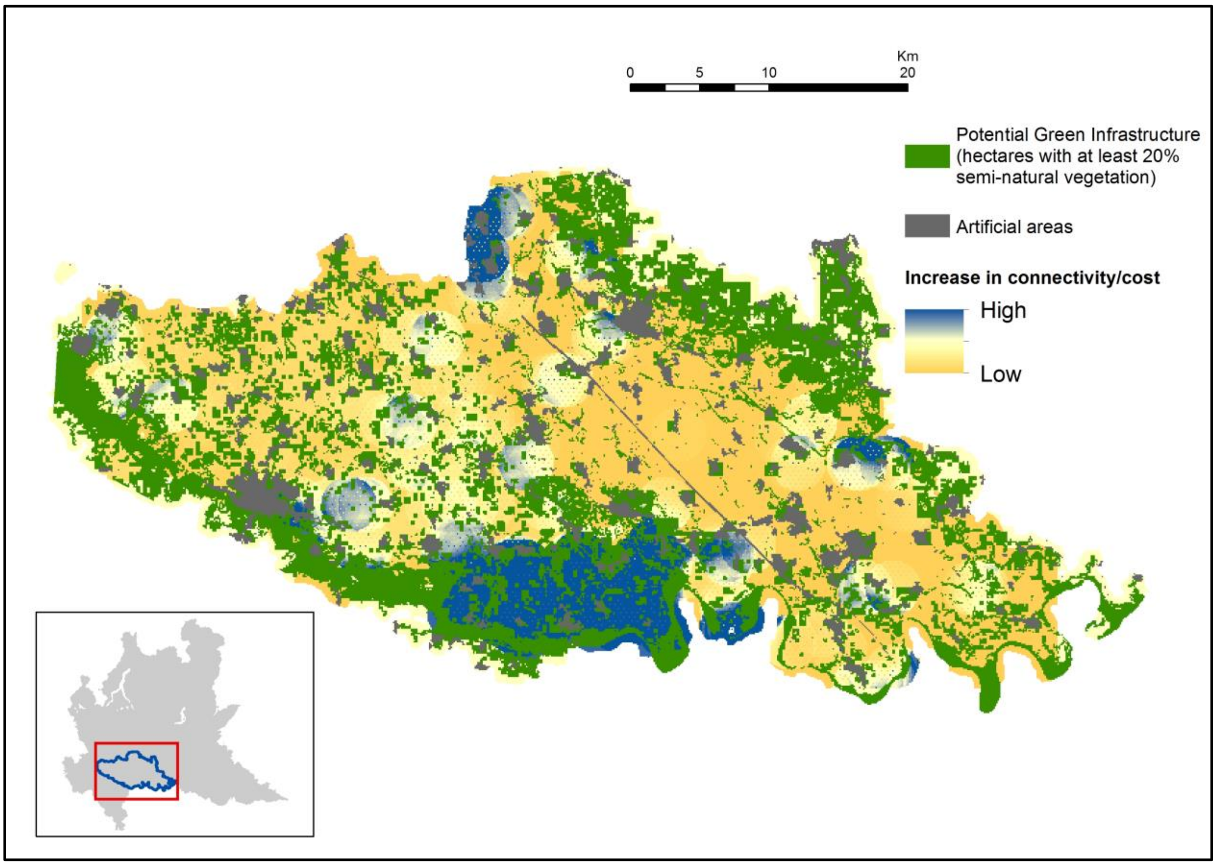


Figure 29. Ratio between node importance for connectivity and cost of conversion by interpolation.

Starting from this "maximum effort" scenarios, other policy alternatives could be considered by visualizing the importance of potential new nodes, both in absolute terms and in relation to the associated cost of conversion. Figure 26 shows the importance of the each new node for the overall network connectivity, defined as the number of the network links intersecting it.

This analysis allowed a better spatial targeting of the measures, by attaching to each new node its potential for enhancing connectivity. By interpolating the results, it was possible to derive a continuous map of increase in connectivity of each non-habitat point in the study area (Figure 27).

These results could be used for instance by managing authorities in the implementation of Rural Development Programs, to define priority scores to rank applications for agri-environmental measures by single farmers, or to identify *a priori* landscape sectors on which to concentrate the efforts for the collective implementation of Ecological Focus Areas. Similarly, they could be used in the frame of land use planning to identify exclusion areas for new developments or infrastructures at the local scale. We elaborated on these aspects in the Discussion section.

A further element to inform policy design and decision making could be the consideration of the cost of conversion to habitat. The importance of the node for each cell was therefore divided by the calculated costs (as defined in section 4.2.3) to obtain a measure of the cost-effectiveness of each potential new node, as shown in Figure 28.

Again, by interpolating the values of the considered cells over the whole study area a continuous map of the cost effectiveness of conversion to habitat could be drawn (Figure 29).

4.3.2 Macro-connectivity analysis at the regional level

The connectivity analysis at regional scale followed the processing steps presented in the flowchart in Figure 14. It was applied to the whole Lombardy and accounted for all hectares of predominant vegetation (SNV14-16), which were spatially contiguous.

The input 'potential GI' layer was obtained from the morphological analysis by considering only 8 connected hectares of SNV with natural share 14-16 (i.e. potential GI *networks*) and excluding *islets*. The resulting 712 *networks* of SNV were further grouped into clusters based on a Euclidean distance of 1 km (top left in Figure 32). This resulted into 238 clusters, for which the macro-connectivity was conducted (green shade in figures 30 and 31). The probability of connectivity between two separate clusters was computed by applying a decreasing exponential function of the effective distance between each pair of clusters. The effective distance depends on the arbitrarily fixed dispersal capability of 'connectivity sensitive' species in a predefined ('moderately' hostile or favourable) landscape. The resistance layer defining the favourable to hostile landscapes of Lombardy was created with increasing resistance values from natural, to agricultural and artificial lands (background layer in figures 30 and 31). The 1/16th shares of each land cover within the hectare cell were translated into one cost as defined in Table 4. As justified in section 1.3 and to suit the computational requirements at the regional scale of analysis, we used 'connectivity sensitive species' eco-profiles (like forest generalist species) and we applied a 50% probability of dispersal for species dispersing 5 km distance in natural lands, 500 m in agricultural lands and 50 m in artificial lands (Table 4).

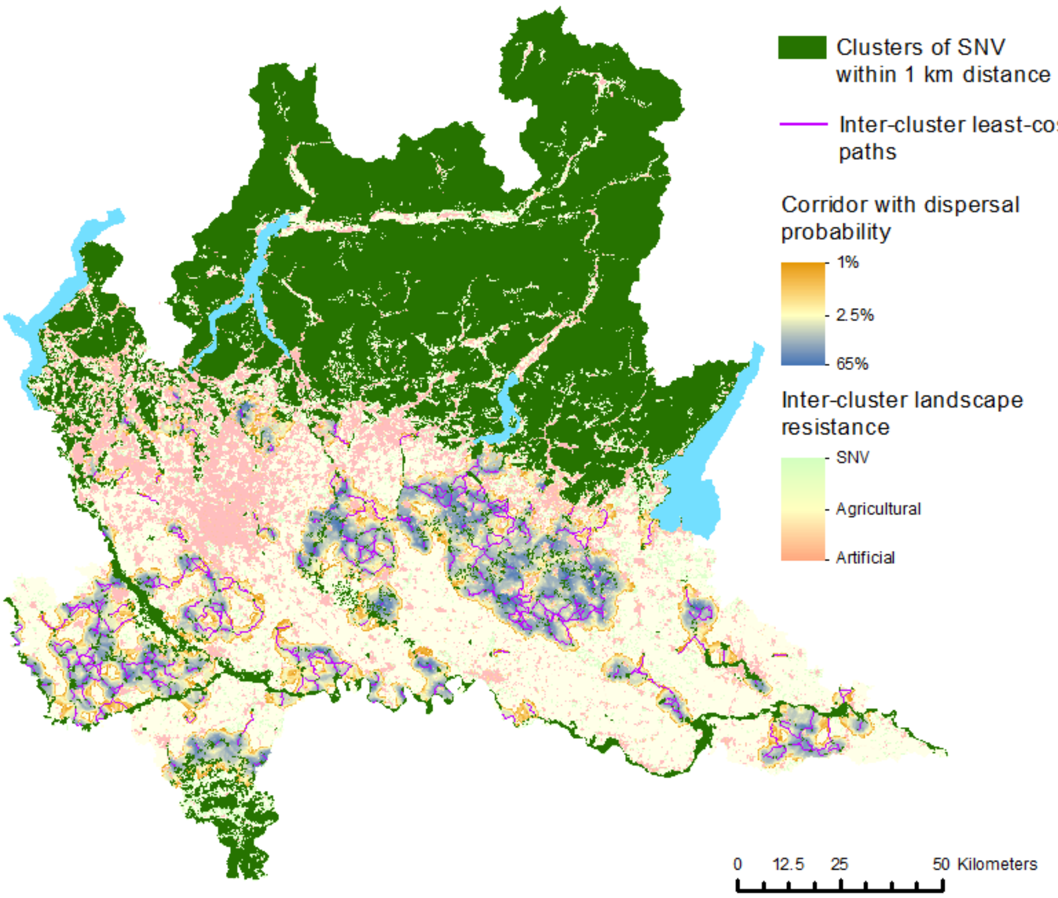


Figure 30. Macro-connectivity of clusters of semi-natural vegetation (potential GI) in Lombardy.

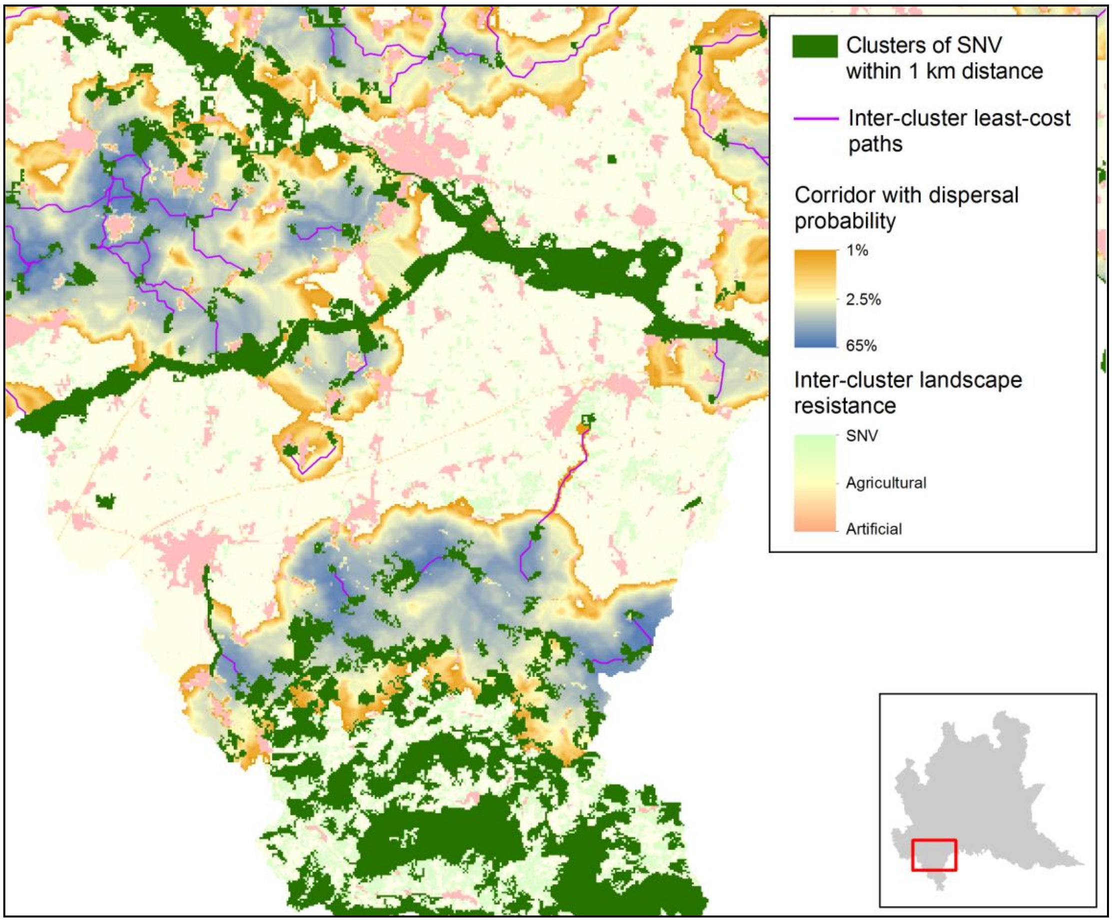


Figure 31. Zoom showing two areas where clusters and their corridors of dispersal are not distant, yet not connected. On the centre, the two corridors of dispersal could be enlarged and connected by natural vegetation within the agricultural lands while on the right it may be difficult due to the barrier of artificial lands.

The least-cost path analysis for the 238 clusters resulted in a total of 28,203 paths that were then reduced to 642 paths, based on a probability threshold of at least 1% (corresponding to a maximum cost of 33,219). The minimum cost among those paths corresponded to a maximum probability of connectivity of 65%.

A network analysis with Conefor software was applied to extract the 366 'used paths' existing in the area delineated between the paths of maximum cost and of minimum cost of dispersal. This exercise enabled the mapping of the corridors of feasible dispersal between the functionally connected clusters, thus providing the delineation of the boundaries of the corridors and the zoning of the dispersal probabilities within them (Figure 30 and 31).

Then, all clusters that were connected by a least-cost path corresponding to a probability greater than 1% were categorised as macro-clusters. A total of 11 'functional' macro-clusters were identified in the region of Lombardy. They were composed by a minimum of 2 clusters and a maximum of 166 clusters; this latter macro-cluster represented the main connected network of natural areas in the Region (Figure 32). 14 clusters were found isolated (probability below 1%).

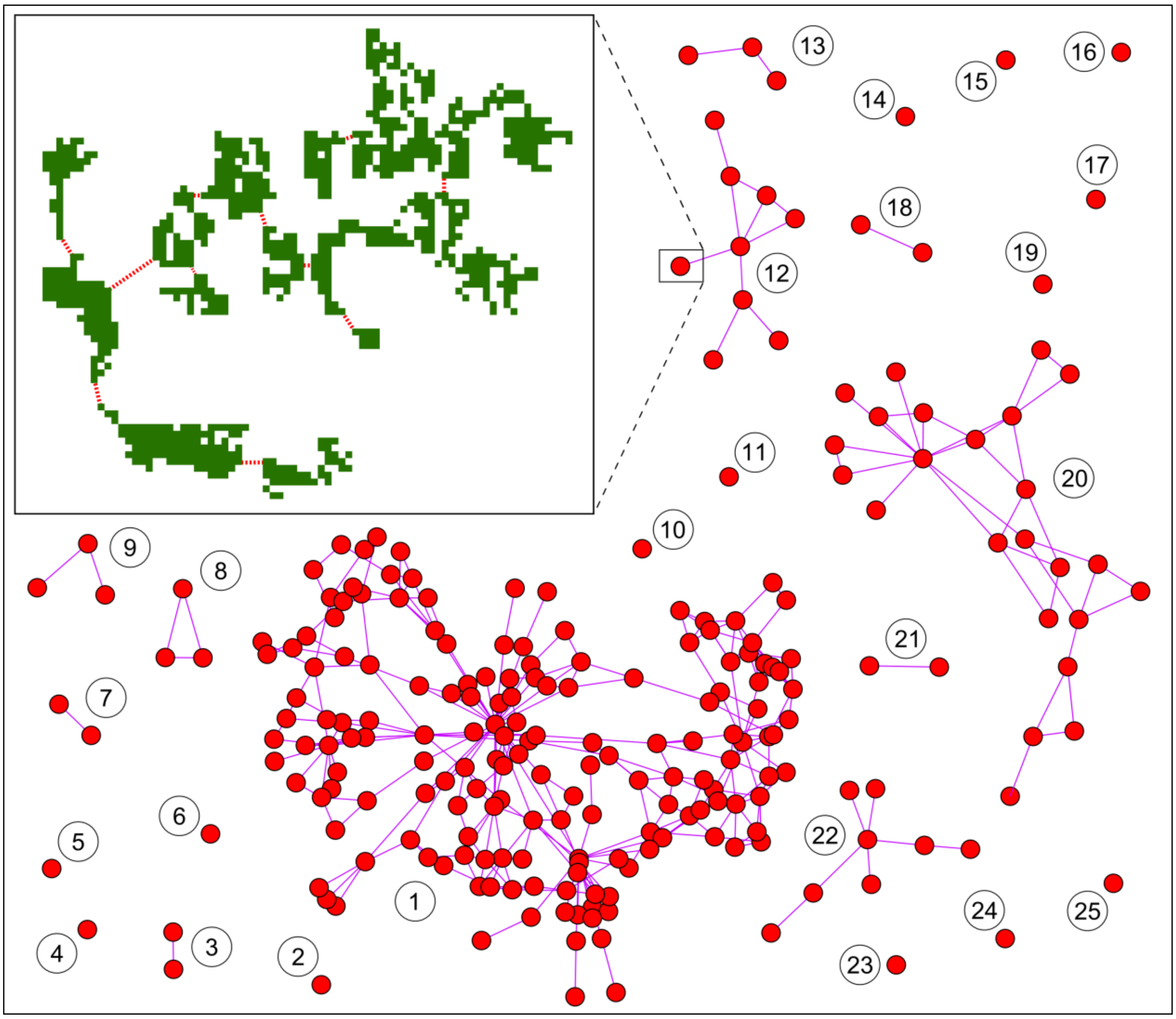


Figure 32. Clusters (red dots) connected by least-cost paths with a dispersal probability higher than 1% (purple links). A total of 11 macro-clusters and 14 isolated single clusters were identified. Each cluster is formed by one or more patches of natural and semi-natural areas closer than 1 km (frame top left).

The final step of the exercise was to enhance the connectivity between macro-clusters and/or isolated clusters. The idea was to assess the monetary cost of connection on which basis the creation of potential connections among macro-clusters and/or isolated clusters would be envisaged. A total of 300 potential paths was selected from the remaining least-cost paths with a dispersal probability below 1%, having the lowest costs of connections between macro-clusters. The monetary cost of connectivity is defined as the cost for converting a share of agricultural area to SNV along the cells over the least-cost path, in order to reduce the landscape resistance and consequently improve the dispersal probability up to the minimum of 1%. A minimum spamming tree algorithm was computed among 300 paths, resulting in the selection of 24 potential least-cost paths with the highest dispersal probability.

Figure 30 provides a new schematic and synoptic view of the potential GI *network* structure among the macro-clusters, facilitating the visualization and interpretation of the results reported on Table 5. For each of the 24 potential paths, the departure and arrival cluster (macro- cluster id) and the number of 1/16 of SNV requested for improving the dispersal probability up to 1% were reported. As expected, the largest macro-cluster (id = 1) was involved in nearly all potential paths.

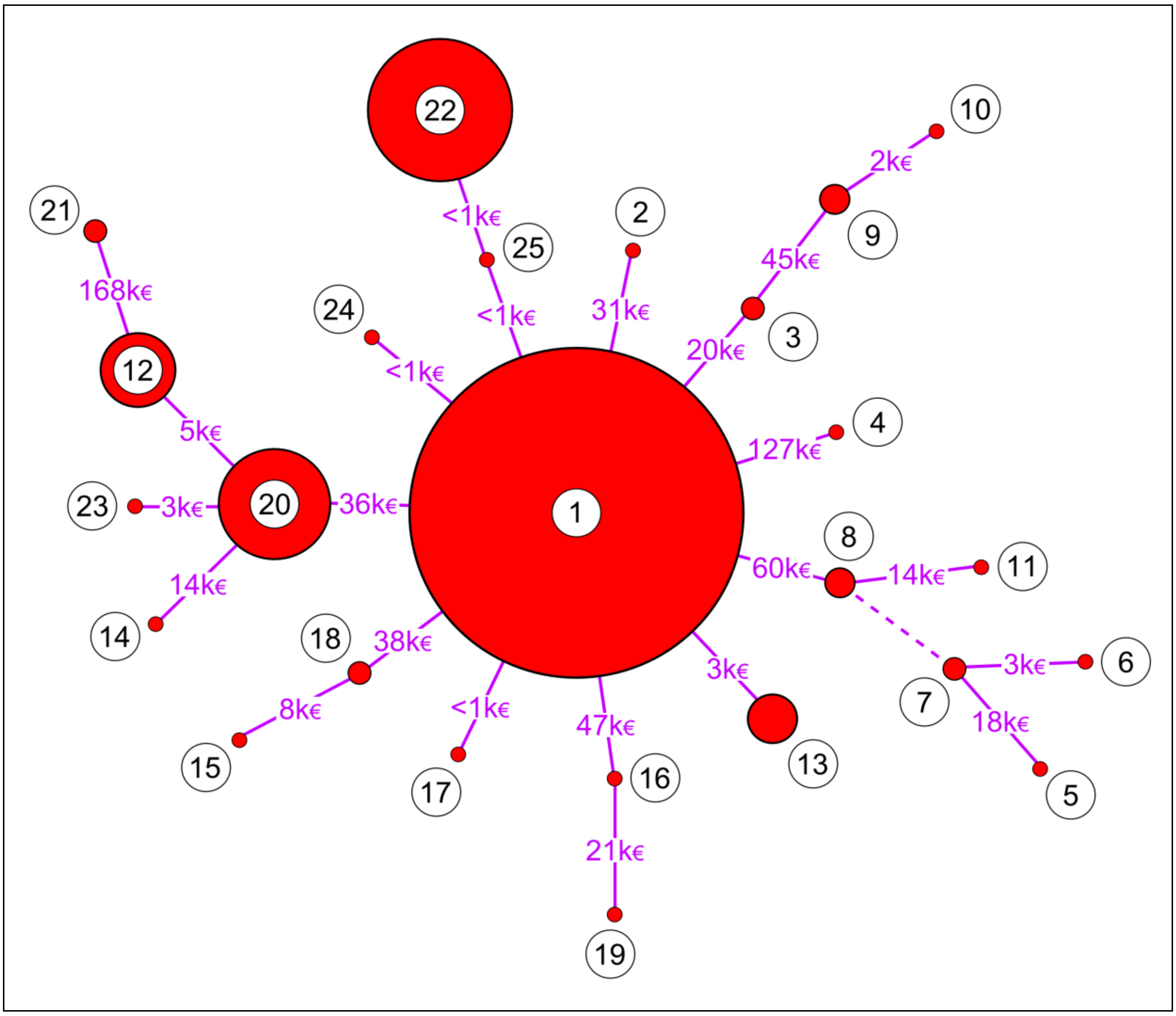


Figure 33. Representation of the 24 potential least-cost paths (purple links) connecting the 11 macro-clusters and 14 isolated clusters (red dots) and their monetary cost in thousands of Euro (k€) for improving the dispersal probability to 1% in Lombardy. The sizes of macro-clusters are proportional to their areas.

The average monetary costs for the conversion of agriculture to SNV along the potential least-cost path were very different according to their location in the Region, varying from a minimum of about 100€ to a maximum of over 2,500€ per 1/16 of SNV. The connection between macro-clusters 7 and 8 was missing, due to the strong urbanization of their surrounding areas that render unlikely any agricultural land conversions.

Potential paths with low connectivity costs or occurring in areas with low monetary cost of conversion represented the most feasible connections; total monetary costs could be even below 1,000 € for their realization. In addition, the computation of a cost/benefit index enabled the identification of potential paths which could provide a higher increment in connectivity once created. In particular, the path from macro-clusters 1 to 20 could connect two large clusters thus improving significantly the connectivity of the whole region; also, the paths linking macro-cluster 1 and 22 and involving cluster 25 could be of interest (see also Figure 33).

Table 5. List of 24 potential least-cost path among macro-clusters and isolated clusters with related monetary cost and cost/benefit index. Highlighted in green and light green the potential paths with the highest cost/benefit indices.

N.	Macro-clusters		Actual path connec-tivity	Missing connec-tivity	N. of 1/16 SNV to be created	Average monetary cost along path	Total monetary cost of path	Connectivity benefit (dPC)	Cost-Benefit index
	From	To							
1	1	2	52021	18802	334.3	1,498 €	31,295 €	0.000127834	305.24
2	1	3	45424	12205	217.0	1,498 €	20,315 €	0.000217346	518.97
3	1	4	186203	152984	2719.7	749 €	127,317 €	0.000042611	101.75
4	1	8	60229	27010	480.2	1,990 €	59,722 €	0.000374709	894.72
5	1	13	55391	22172	394.2	106 €	2,611 €	0.001322977	3158.97
6	1	16	49948	16729	297.4	2,539 €	47,194 €	0.000030092	71.85
7	1	17	33773	554	9.8	406 €	250 €	0.000046670	111.44
8	1	18	46731	13512	240.2	2,501 €	37,548 €	0.000112961	269.73
9	1	20	48442	15223	270.6	2,145 €	36,281 €	0.031785692	75896.95
10	1	24	33759	540	9.6	492 €	295 €	0.000121747	290.70
11	1	25	34714	1495	26.6	185 €	307 €	0.000616081	1471.06
12	3	9	60219	27000	480.0	1,498 €	44,940 €	0.000002284	5.45
13	5	7	44006	10787	191.8	1,498 €	17,954 €	0.000000007	0.02
14	6	7	35270	2051	36.5	1,498 €	3,414 €	0.000000010	0.02
15	7	8	63291	30072	534.6	-	-	0.000000654	1.56
16	8	11	39355	6136	109.1	1,982 €	13,513 €	0.000000724	1.73
17	9	10	34356	1137	20.2	1,498 €	1,892 €	0.000000058	0.14
18	12	20	35449	2230	39.6	2,162 €	5,357 €	0.000158871	379.35
19	12	21	102741	69522	1235.9	2,173 €	167,857 €	0.000000297	0.71
20	14	20	38933	5714	101.6	2,184 €	13,866 €	0.000001840	4.39
21	15	18	36391	3172	56.4	2,137 €	7,532 €	0.000001367	3.26
22	16	19	40567	7348	130.6	2,539 €	20,730 €	0.000001687	4.03
23	20	23	34516	1297	23.1	1,774 €	2,557 €	0.000003470	8.29
24	22	25	35869	2650	47.1	115 €	339 €	0.000552940	1320.29

5 Discussion

This study focuses on the identification of existing corridors for species with different dispersal ranges (insect, mammals), the identification of gaps, and the proposal for solutions to improve existing connectivity, including the monetary cost of taking such actions. Connectivity is addressed in the study as a recommended functional attribute of the GI, and this requires the analysis to be carried out at the appropriate landscape scale.

Management practices taking into consideration the landscape matrix are increasingly considered in regional programs for rural development, sustainable land use, and land use planning. The analysis considered semi-natural vegetation (SNV) elements as potential GI components and interestingly, SNV included forests and other wooded lands but also 'trees outside the forest', semi-natural grasslands in arable lands, and other non-woody vegetation. Transport infrastructure, settlements and intensive agriculture were considered as the main GI antagonist elements in the landscape, the latter being also the land use that can contribute the most to an improvement of GI connectivity through conversion of selected cropped areas to SNV. This broad generic characterisation of the landscape matrix into beneficial and deleterious lands to nature (GI) is in line with the one proposed by European Environment Agency (2014a) to set priorities areas for conservation and restoration. The current approach could be further improved by considering protected areas boundaries and also qualitative attributes of vegetation (for example, forest canopy closure and development stage, plantations of exotic or native species, degraded ecosystems).

A new high resolution land cover data was created to capture small potential GI elements i.e. riparian forest, hedgerows, extensive grassland. By upgrading the level of spatial and thematic detail obtained from the traditionally used CORINE Land Cover classes, this new data layer particularly reduces the overestimation of GI in naturally dominated landscape matrix and its underestimation in fragmented landscapes. It is suitable to map fragmented landscapes with heavily modified ecosystems, such as lands mainly occupied by agriculture where SNV elements have been reduced in the last decades or lands where grey infrastructure (settlements and roads) constitute obstacles to the inter-linkage of 'green' spaces. This new layer allows a more accurate spatial-targeting of priority areas where GI connectivity should be enhanced. Still, the spatial resolution of the grasslands layer (100 m) was lower than the one for forests and grey-infrastructure (25 m). This is the main reason why GI was defined based on the SNV share per hectare (100x100 m). This could be improved in the near future when the high resolution map of semi-natural grasslands will be available at 20 m from the Copernicus Programme. Another reason of using hectare units was the data resolution on the monetary cost of conversion of agriculture to vegetation, that was used to link to the benefit in connectivity. This cost was obtained per hectare by downscaling the agricultural gross margin layer provided by the Common Agricultural Policy Regionalised Impact (CAPRI) model, currently available at the spatial resolution of the Homogeneous Spatial Mapping Units (1 km^2).

The modelling framework available at JRC is based on GUIDOS Toolbox, Conefor software and Python programming tools and was adapted for GI purposes. It was enriched by a refined landscape mosaic model, a new corridor mapping tool and a cost-benefit function. The landscape mosaic model was refined in order to better characterise fragmented landscapes with low presence of SNV, *i.e.* dominated by GI antagonist component. The morphological analysis enabled the characterisation of potential GI components into *islets* and *networks* made of *compact* patches and *linear* features. Having identified connectivity as a recommended functional attribute of the GI, we assumed that *networks* of SNV formed the core of the potential GI and that *islets* could become part of it when appropriately connected. The landscape mosaic pattern was relevant to identify the most 'exposed' components e.g. *islets* and *linear* features of vegetation isolated in hostile (non-GI) landscapes. Corridors (area) most favourable to species dispersal in between clusters of SNV were mapped, instead of solely least cost paths as previously done in the connectivity model. Corridor boundaries were delineated by the lowest acceptable probability of dispersal of 1% and by the maximum probability, calculated on the basis of the actual landscape resistance. One could argue that 1% of probability is very low but this threshold could easily be changed by the user. In order to mitigate fragmentation by hostile land uses, corridors maps could provide guidance on areas where to increase the spatial and functional connectivity between *networks* and *islets* (within corridors), and areas where to promote land use development such as grey infrastructure and intensive land use (outside corridors). Corridor maps could support the forest sector on targeting areas where to limit intensive forestry practices, where preferably promoting practices in line with species requirements, where privileging more forest conservation than accommodating interests of sectors such as bio-energy.

To further enhance the connectivity of GI, the cost-benefit function considered the gross agricultural margin (including subsides from CAP's first pillar) to estimate farmers' foregone income, hence the monetary cost for the society to enhance the GI. This indicator was selected as a general metric, available for the whole EU, and reflecting the rationale of European Regulation 1305/2013. It represents an annual cost, to be paid yearly for the entire period of farmer's commitments (usually, not less than 5 years). Again, the cost function could be easily changed in the model if more detailed information would be available at local scale, for example the exact amount of premiums established by individual Managing Authorities for agri-environment-climate commitments. Concerning Pillar 1, this exercise was run with pre-Greening data. Nevertheless, under the current CAP programming period (2014-2020) the gross margin would include the Greening Payments.

Regarding computation and processing times, the morphological analysis and the landscape mosaic pattern exercises were straightforward and quick (in the range of seconds or minutes) while the connectivity analysis could take few days. To enable the processing in reasonable time (hours up to maximum three days), some choices were made.

Some comments on what is considered connected shall be pointed out before discussing possible refinements of the connectivity analysis. In this exercise, the minimum cell resolution was one hectare (100 m x 100 m, made of sixteen 25m pixels (4 x 4)) meaning we assumed that i) the vegetation when present within one cell (quantified by a 16th share) was considered internally connected regardless of the actual spatial distribution of the vegetated pixels composing the cell ; ii) in the local scale micro-connectivity analysis focused on small flying insects, an isolated small vegetated patch (low natural share of 3/16 of an hectare) was considered sufficient to support functional biodiversity and could act as a key component in the potential GI *network*; iii) in the regional scale macro-connectivity analysis focused at 'connective sensitive' terrestrial species with intermediate dispersal capability, only hectares of land where vegetation was predominant (natural shares of at least 14/16 of an hectare) could act as key components in the potential GI *network*, while smaller vegetated patches (low natural share per hectare) and isolated patches (*islets*) could support functional biodiversity but were accounted in corridors between *networks*. The assumption for the micro-connectivity study is realistic since it was focused on small organisms (insects) able to fly up to 540 m, but the threshold of natural share in one hectare, currently set at 3/16 (=0.1875 ha = 1,875 m^2), may need to be increased in the case of other species (e.g. birds). Also, this assumption was based on studies estimating the quantity of uncultivated land (fallow, SNV) in the agricultural matrix necessary to support biodiversity and (mainly) pollination and biological control. However, what such studies do not explicitly evaluate whether such ratio is scale-invariant, *i.e.* if there is an absolute threshold below which functional biodiversity cannot be supported. In the macro-connectivity analysis, we considered terrestrial species for which the landscape resistance matters more than for flying organisms. We assumed species dispersing in average 50 m in artificial, 500 m in agriculture up to 5 km in natural areas. The 500-1000 m dispersal capability is supported by a review of most frequent upper limit of distance thresholds in seven types of dispersal mode (seeds and animal vectors of dispersal) by Vittoz and Engler (2007). Opermanis et al. (2012) also suggested a maximum distance of 1 km between 'habitat' sites as the one reflecting well the maximum dispersal capacities of most taxa. The exclusion of hectares of lands with low natural share as component of the GI *network* can be considered realistic since the presence of artificial land (more than 2/16 of an hectare cell and contiguously distributed) may significantly hamper dispersal of terrestrial species.

The main computing limitation concerned the calculation of connectivity among large number of components of potential GI *networks*, in particular for the mapping of least-cost paths and corridors in between *networks*, and for the calculation of node (component) importance. At regional level, only GI *networks* (thus excluding *islets*) were retained as nodes in the calculation of connecting paths. As said before, *islets* whose number could reach 15,000 or even more in this case study, were accounted in the calculation with the lowest landscape resistance along the paths between *networks*. In addition, *networks* were regrouped into clusters when they were apart less than one kilometre distance meaning that those *GI networks* were considered connected regardless the landscape matrix resistance in between them. This clustering operation based on the 'one kilometre apart' criteria, although acceptable, remains a main limiting factor to be taken into account and that could be revised as soon as computing capacities would be improved. In this exercise, the number of GI *networks* was around a thousand and was reduced to circa 240 when clustered. Corridors were then easily calculated between clusters. Even at sub-regional level (NUTS3), the number of nodes could easily reach the order of magnitude of 10^4, making computational times very long. At local scale, we used the number of used links (number of links from/to each cell multiplied by the times they were used in the computation of the network connectivity), as a proxy for the "node importance". In this case study, this approximation was acceptable, but this remains a main limiting factor to be taken into account.

Finally at local scale, we considered functional connectivity for flying insects such as bees, ladybugs or other predators that deliver pollination and biological control, which are relevant ecosystem services for agricultural production, though the aim here was not to precisely model and quantify such services. In the case of pollination, spatially explicit models already exist (Londsdorf, 2009; Zulian et al., 2013) and they can be used to provide a more detailed quantification of the pollination potential in a given land cover configuration and in different scenarios. Nonetheless, the underlying assumption shared by the method used in the present exercise and those models is that such organisms can disperse from one habitat point in the landscape with a probability function that decreases with distance and depends on their functional traits, as the typical and maximal foraging distance. Similarly, at regional scale, the macro-connectivity approach was demonstrated for 'connective sensitive' terrestrial species of intermediate dispersal capabilities and for which infrastructure (artificial lands and roads) and intensive agriculture with little or no SNV elements pose the biggest threats to their dispersal. We assumed that at this scale, their needs in terms of favourable landscape would likely benefit a large range of species. The approach does not replace available ecological modelling tools of connectivity (see references in European Environment Agency, 2014; Jongman et al., 2011) that would represent better the connectivity needs of specific ecoprofiles of group of species (McHugh and Thompson, 2011; Bergsten et al., 2013). However, those models require time and heavy computing power spent researching, constructing and 'running' ecoprofiles and detailed knowledge on species is not always available.

6 Policy recommendations

This study is exploratory, the intent being to show the potentialities of considering the structural continuity and functional connectivity of semi-natural vegetation (SNV) to support the design and implementation of GI as a "*strategically planned network of natural and semi-natural areas"*. Lombardy was used as a pilot region, as being representative of a wide range of landscapes, *i.e.* agrarian intensively used and fragmented landscapes in the plains, mixed natural and intensively used landscapes in the Alpine foothills and predominant natural landscapes in the highlands. Corridors most favourable to species dispersal were mapped and gaps in connectivity were identified. Spatially explicit solutions were then proposed to prioritise improvement actions based on their monetary cost through payments of 'greening' subsidies and their benefit for connectivity. This was demonstrated at local scale to benefit pollinators and pest predators and at regional scale to benefit 'connective sensitive' terrestrial species. A new schematic representation of GI was proposed to give a synoptic view of the existing GI *networks* in the region and their cost effective potential development to enhance connectivity. The approach contributed one possible spatially explicit tool to measure how GI *"provide ecological, economic and social benefits*". The consideration of both ecological and economic aspects, although restricted to aspects of connectivity and the cost of 'greening' subsidies would allow authorities and land managers to identify the most cost-effective way of spatially targeting forestry and agri-environmental measures, and thus strengthen their integration and coherence.

The presented approach should be seen as a rapid assessment tool to gain an additional insight on the structural continuity and functional connectivity of potential GI "green" terrestrial components from a generic perspective and with focus on most hostile land uses to a GI implementation. The proposed approach remains sufficiently general to be applicable under different environmental conditions, but could be integrated to suit local or regional needs by taking into account specific ecoprofiles and more detailed habitat characteristics (species distribution, habitat condition etc.). It provides an additional micro and macro-scale connectivity layers worth considering to better integrate landscape planning, forestry and agriculture with emphasis on ecosystem functioning. It also addresses the methodological needs on how accounting for connectivity to mitigate fragmentation due to land use intensification and development and prioritize ecosystem improvement actions.

The exercise shows that connectivity analysis can indeed support the design and the implementation of the GI in rural settings and particularly agricultural landscapes. An appropriately connected GI at local scale is in fact essential to guarantee the supply of ecosystem services such as pollination and pest control over the agricultural area. The fields of application are manifold: first and foremost, the Rural Development Policy and in particular agri-environmental measures in favour of biodiversity. Measures involved under CAP Pillar 2 cover, among others, subsidies for organic farming, payments under Natura2000 and payments for the development of woodlands, their conservation and improvement of their viability (such as afforestation, restoration, pest control). Improving spatial targeting of agri-environmental measures is highly advocated by the literature (see e.g. European Court of Auditors, 2011; Piorr and Viaggi, 2015 and references therein) and connectivity surely is a key element to be taken into account to this end. The consideration of both environmental and economic criteria in the implementation of such measure is also in line with art. 49 of EU Regulation 1305/2013 on support to rural development, which states that (paragraph 1) "*the Managing Authority of the rural development programme shall define selection criteria for operations* […] *to ensure equal treatment of applicants, better use of financial resources and targeting of measures in accordance with the Union priorities for rural development*"; and (paragraph 3) "*Where appropriate, the beneficiaries may be selected on the basis of calls for proposals, applying economic and environmental efficiency criteria*.".

Connectivity analysis could also support the identification of larger areas where commitments undertaken jointly by groups of farmers and forest owners would synergistically enhance the environmental and climate benefit, again as advocated by scientific literature, by EU Regulation 1305/2013 (*considerandum* 22; art. 35 (g)) and in support of collective implementation of Ecological Focus Areas, in particular permanent structures such as hedges, trees in groups, in line or isolated, and afforested areas. In the case study presented here, for instance, clusters where high improvements of connectivity could be achieved were identifiable (see Figure 29) in the South-eastern part of Lombardy, where cost-effectiveness of interventions would be relatively high as well.

This GI spatially-explicit priority frame could facilitate and thus encourage the cooperation between advisory and service organisations of the agricultural and forestry sectors as well as between farmers and forest owners. The consideration of both the ecological and economic dimension would allow the managing authorities and land managers to identify the most effective way to pursue different policies. In case of a limited fixed budget, interventions could be prioritised according to their cost effectiveness; where budget is not the main limiting factor, they could be ranked according their absolute contribution to habitat connectivity. Vice versa, a minimum level of connectivity could be established a priori and the main policy goal and the analysis carried out would allow to determine the most efficient way to reach it. In other cases, the policy designers could be interested in minimizing the loss of cultivated land instead of agricultural revenues. The maps over Lombardy presented in figures 28, 29, 31 and 33 represent interesting tools on this respect for guiding cost-effective forest and agri-environment interventions. Besides this, such maps could also support the spatial-planning of the most intense, permanent and aggressive changes in the landscapes such as transport infrastructure and peri-urban development that likely have the largest effects on connectivity. Policy makers would then ensure that such abrupt changes do not occur along new potential cost-effective corridors and within macro-clusters of potential GI *networks* of a region. Furthermore, such maps available at local and regional scales could facilitate the incorporation of connectivity-related considerations in agri-environment, forest management and planning and contribute solving the potential mismatch between the usual scale for forest planning (forest ownership or stand) and the wide spatial scales at which ecological connectivity could be better considered and influenced.

Finally, Forest and Rural Development Policy are not the only field of application of this analysis: urban and landscape planning may also benefit from it, particularly when assessing the impacts of new urban developments and infrastructures and the implementation of mitigation and compensation measures i.e. creation of new green urban areas, habitat restoration, brownfield remediation.

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List of abbreviations and definitions

CAP: Common Agricultural Policy

CLC: Corine Land Cover

FAO: Food and Agriculture Organization

GI: green infrastructure

HRL: High Resolution Layers

JRC: Joint Research Centre

MMU: minimum mapping unit

PC: Probability of Connectivity

RAPC: Root un-weighted Average Probability of Connectivity

RPC: Root Probability of Connectivity

SNV: natural and semi-natural vegetation

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