LUIGI WP1 Technical Annex: Mapping a Green Infrastructure network in the Alpine Space: a case study of the LUIGI pilot regions

Annex to D.T1.2.1- Enhancing landscape multifunctionality and ecological connectivity across the Alps. Interreg Alpine Space project n. 863 "LUIGI"- Linking Urban and Inner-Alpine Green Infrastructure – multifunctional ecosystem for more liveable territories.

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Introduction

This annex aims to provide technical guidance to practitioners, spatial planners and researchers aiming to establish a green infrastructure network in the Alpine region and beyond. Here we illustrate the framework and methodology adopted by our team whilst identifying Green Infrastructure networks in diverse alpine regions as part of the Interreg Alpine Space project n. 863 "LUIGI"- Linking Urban and Inner-Alpine Green Infrastructure – multifunctional ecosystem for more liveable territories.

This reports firstly provides an overview on the methodological framework developed, and then gives detailed information on how we carried out the ecological connectivity and ecosystem services-based multifunctionality assessments. We hope that you will find this report useful for better understanding the assumptions and the data behind the maps developed by our team (geo data available at: https://doi.org/10.5281/zenodo.6602481) during the LUIGI project. For an overview of the results of our mapping, please refer to the pilot region-specific policy briefs (D.T1.2.1 available on the LUIGI website).

Mapping a Green Infrastructure network in the Alpine Space

The present approach for the identification of Green Infrastructure components is based on the most recent spatial data and methodological developments presented in a joint report of the European Commission's Joint Research Centre (JRC) and European Environmental Agency (EEA) (Estreguil et al., 2019), and in technical reports developed by the EEA and its European Topic Centre on Urban, Land and Soil Systems (ETC/ULS) (EEA, 2014; Carrao et al., 2020). These reports provide indications on how to map Green Infrastructure networks that, building on designated protected areas, complement the network with other key natural and semi-natural features that support the movement of medium-large mammal species and the delivery of ecosystem services. In line with Estreguil et al. (2019), we adopt two complementary approaches: a physical mapping which identifies protected areas, ecological networks, and other valuable natural areas, and a functional, ecosystem services-based mapping which ensures the delivery of provisioning, regulating and cultural services. Following the European Commission's definition of Green Infrastructure as an *interconnected* network which provides *multiple services*, we identify Green Infrastructure based on an **ecological connectivity assessment** and an **ecosystem services-based multifunctionality assessment**.

- **The ecological connectivity assessment** allowed to identify the ecological corridors that best connect core habitat areas with high ecological value (Ecological Conservation Areas).
- **The ecosystem services-based multifunctionality assessment** allowed to identify multifunctional areas that have the highest capacity to support multiple ecosystem services. Areas that displayed the highest (top 10%) multifunctionality values were deemed to be hotspots of multifunctionality.

(Please read the following sections of this document to understand the methodology used for identifying ecological corridors and top multifunctional areas.)

The components of the Green Infrastructure networks considered (Figure 1) in the LUIGI project are:

- **Ecological Conservation Areas** that include protected areas and other valuable natural areas. These core areas constitute the backbone of the Green Infrastructure network and should be protected and managed with particular attention. These areas were already identified and mapped by the Interreg Alpine Space project Alpbionet 2030.

- **Ecological Corridors** that connect Ecological Conservation Areas. Connecting features can be part of the existing landscape which needs to be conserved (e.g., a forest), or features that should be restored to a more natural state to close gaps in the network (e.g., small/degraded wood in the valley floor). In some cases, it might be necessary to establish wildlife crossings. Corridors should be managed to ensure the effective movement of forest based, medium-large mammal species.
- **Multifunctional Areas** that include the areas in urban, agricultural, forested, and open areas displaying the highest ecosystem services-based multifunctionality values (top 10%). These multifunctional areas should be preserved and managed with particular consideration.

Note: practitioners implementing Green Infrastructure networks in their regions should also include locally protected habitats and consider the requirements of local animal and plant populations that are not directly addressed by the present transboundary approach (e.g., birds, non-forest mammal species etc.).

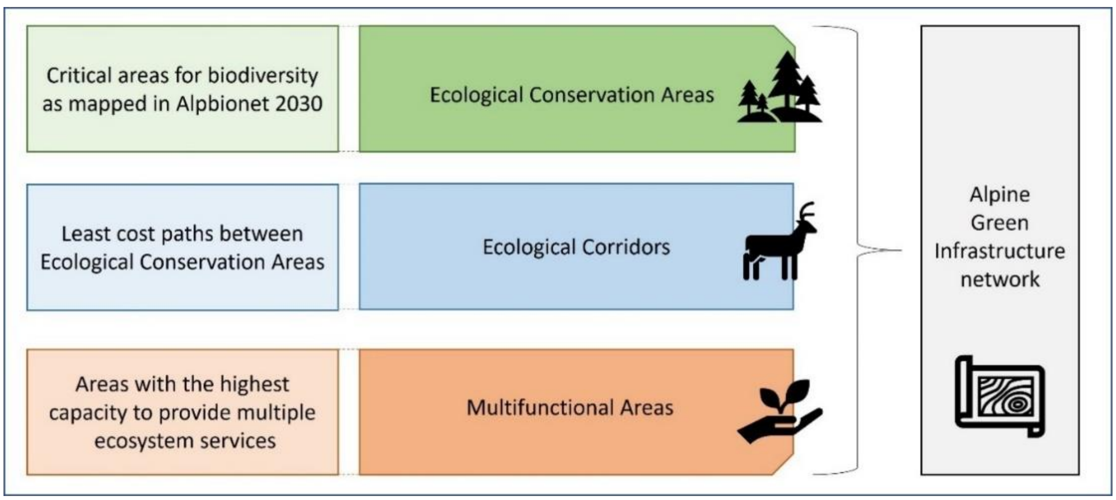

Figure 1. Methodological approach for identifying Green Infrastructure networks in regions of the Alpine space. Ecological corridors connecting conservation areas with high ecological value support biodiversity and the viability of animal populations. On the other hand, multifunctional areas provide multiple ecosystem services and contribute to address multiple societal challenges.

Following the definition of Green Infrastructure, the results of the ecological connectivity and multifunctionality analyses can be combined to identify areas that could become part of a Green Infrastructure network. Merging these two components into a composite bivariate map can show the potential capacity of ecosystems across the LUIGI pilot regions to simultaneously support ecological connectivity and ecosystem services at different levels (Figure 2c).

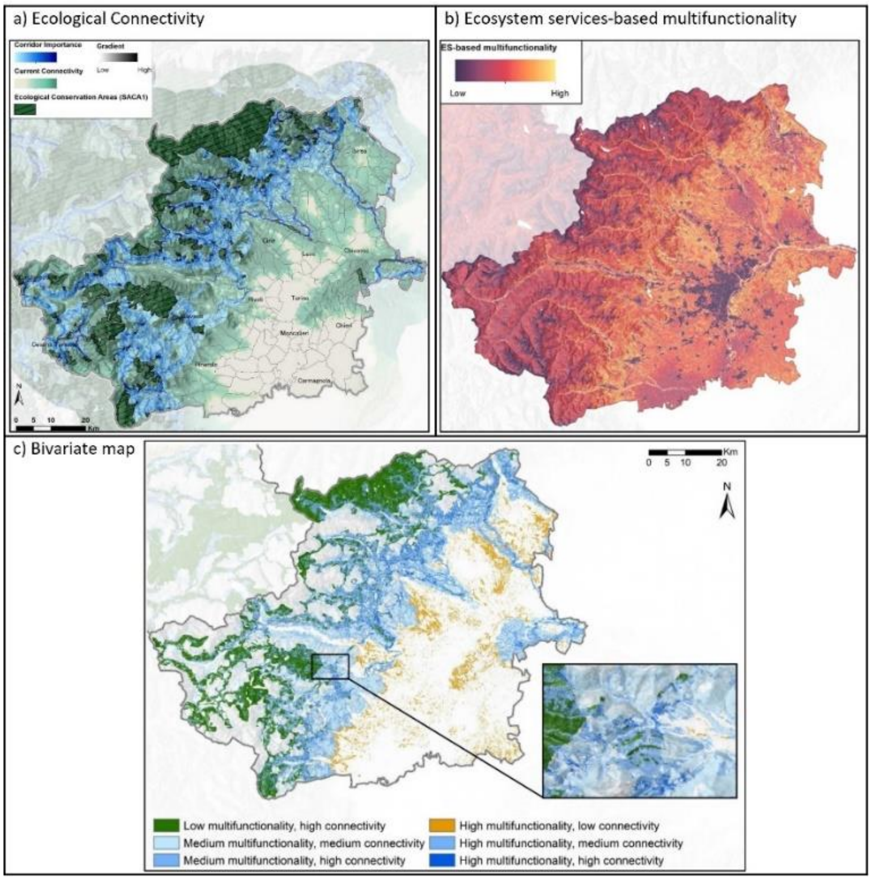

Figure 2 illustrates how the ecological connectivity (a) and ecosystem services-based multifunctionality (b) assessments can be merged in a bivariate map (c) to identify synergies and those areas that provide ecosystem services and act as corridors at the regional level. The region of the metropolitan city of Turin (Italy) is brough as an example to illustrate the results.

These results can support landscape planners and decision makers in identifying priority areas for intervention as well as critical areas that should be protected or sustainably managed. Moreover, these maps on ecological connectivity and multifunctionality can be overlayed with other information available at regional level (such as protected areas, properties receiving subsidies, areas under landscape and zoning regulations, transport infrastructure, road kills etc.) to support regional territorial planning and identify strategic and critical areas that could become part of a regional Green Infrastructure network.

Scale of the analysis

One of the aims of this study has been to find a compromise between the spatial resolution used for the analysis, and the extent of the area analysed. In LUIGI, we decided to carry out our analyses at high resolution (25 m) over the administrative NUTS3 regions (Nomenclature of Territorial Units for Statistics) involved in the project (Figure 3), as they represent a suitable scale for addressing urban-rural linkages, given that they often feature big cities and the surrounding rural and alpine areas, and that land management regulations often occur at this scale.

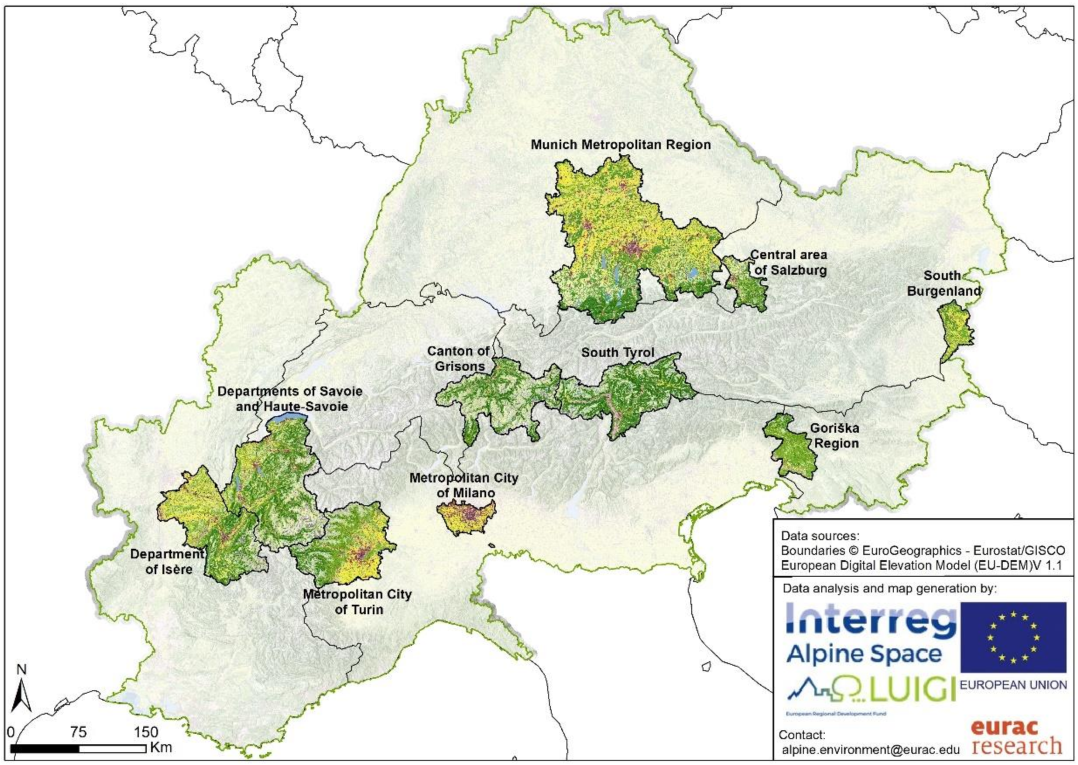

Figure 3 Regions of the EUSALP macro-region that have been analysed in the LUIGI project. Clockwise, starting from the west, we can find the department of Isère (FR), departments of Savoie and Haute-Savoie (FR), the Munich Metropolitan Region (DE), the Central Area of Salzburg (AT), South Burgenland (AT), the Goriška region (SI), South Tyrol (IT), the canton of Grisons (CH), the Metropolitan City of Milan (IT), and the Metropolitan City of Turin (IT).

Data available on the LUIGI geodatabase

The data available on the geo database (https://doi.org/10.5281/zenodo.6602481) consist of:

- **Raster of the ecosystem services-based multifunctionality** of the LUIGI pilot regions.
  This raster (10 m) contains the ecosystem services-based multifunctionality values of the LUIGI pilot regions. Values are comparable across pilot regions. Values are integers numbers stretching between 0 and 90.

- **Raster of the Ecological network** of the LUIGI pilot regions.
  This raster (20 m) contains the main elements of the LUIGI pilot regions' ecological network and of the main results of the ecological connectivity assessments. Raster values are 1,2,3,4,5,11,12:
  - 1 - **Core areas to be conserved**
    Ecological Conservation Areas and surrounding areas (pixels with cost-weighted distance (CWD) values between 0 and 2500).
  - 2 - **Areas supporting ecological connectivity**
    Areas neighbouring ecological conservation areas that support connectivity (pixels with a CWD >2,500 and <25,000)
  - 3 - **Areas where connectivity can feasibly be restored**
    Areas where connectivity could be restored or greatly improved with ecological restoration, planting of hedgerows etc. (pixels with CWD >25,000 and <80,000)
  - 4 - **Areas with low ecological connectivity**
    pixels with CWD >80,000 and <250,000
  - 5 - **areas with no ecological connectivity**
    pixels with CWD >250,000

  - 11 - **corridors bottlenecks to be protected/restored**
    Sections of the modelled ecological corridors that are particularly critical because a high flow of animal movement was modelled there. These areas should be managed to ensure the movement of animals by restoring ecosystems to a natural state and creating wildlife over/under passages. (Pixels of the Pinchpoint raster in the 66th percentile/top third).
  - 12 - **corridors supporting animal movement**
    Areas of the modelled corridors that support connectivity (for example, forests leading to a corridor bottleneck) (Pixels of the Pinchpoint raster below the 66th percentile- lower two thirds)

- **Landscape Resistance Raster** of the LUIGI pilot regions (+ buffer).
  This raster (20 m) can be used as input file for Linkage Mapper or other tools based on cost-weighted distances (the opposite of this raster can be used as habitat suitability). Cell values represent the cost or resistance of each 20mx20m pixel to animal movement. The value is the mean of sixteen 5mx5m pixels of the EUSALP high resolution land use map reclassified using the values of table 2. Values are integer numbers stretching from 1 to 1000.

For more data, contact:
Eurac Research, Institute for Alpine Environment - alpine.environment@eurac.edu

Mapping ecological corridors between Ecological Conservation Areas

Green Infrastructures networks are considered effective conservation measures as they connect existing protected areas, increasing the habitat available to species and favouring the degree of ecological connectivity between bigger core habitat areas. Ecological connectivity, defined as the ability of animals to move through the landscape (Taylor et al., 1993), is critical for maintaining animal populations genetic diversity and metapopulations viability, and allowing species to shift their geographic range in adaptation to climate change (Cushman et al. 2013).

Green Infrastructure networks support biodiversity conservation by both providing favourable habitats and acting as ecological corridors (EEA, 2014). Areas with high ecological value and limited anthropic disturbance such as protected areas, forests or alpine meadows, provide habitat to many flagship and common species of the alpine region. Moreover, linear landscape features, such as hedgerows and riparian vegetation or small woods acting as stepping-stones, can help some animal species move across anthropized areas (such as intensively used agricultural areas), allowing them to reach new habitats, resources, and mates.

LUIGI and AlpBionet 2030

One of the aims of the mapping effort carried out in the LUIGI project has been to identify in each LUIGI pilot region ecological corridors that can connect areas with high ecological value, such as protected areas. The identification of regional corridors in the LUIGI pilot regions builds on the work done by the Interreg Alpine Space project Alpbionet 2030, which assessed the capacity of the EUSALP area to support ecological connectivity and subsequently identified three classes of Strategic Alpine Connectivity Areas (SACA): Ecological Conservation areas, Ecological Intervention Areas and Connectivity Restoration Areas.

Table 1 Strategic Alpine Connectivity areas identified in the Interreg Alpine Space project "Alpbionet 2030"

Strategic Alpine Connectivity Areas	Description and management recommendations
Ecological Conservation Areas (SACA 1)	Areas that still have considerable space for connectivity with non-fragmented surfaces and where connectivity needs to be conserved. Such areas are characterized by a sparse infrastructure, dispersed settlements and large natural areas at mid-altitude. Actions: a well targeted large scale conservation policy is recommended (passive approach).
Ecological Intervention Areas (SACA 2)	Areas with high potential for connectivity in which larger, more or less natural non-fragmented zones could easily be created, especially by connecting protected areas, Natura 2000 sites or other precious biotopes. Actions: a spatial planning policy aiming at the creation of large scale non-fragmented areas is recommended (active approach) but also single action like to creation or restoration of wildlife passages.
Connectivity Restoration Areas (SACA 3)	Areas where fragmentation has already progressed so far that interlinked habitats and a transparent landscape matrix are no longer a realistic option using reasonable, viable interventions. Actions: ad hoc measures to improve ecological connectivity are recommended (punctuated approach)

In the LUIGI project, we aimed to provide detailed recommendations to spatial planners and policy makers of the LUIGI pilot regions on how to prioritize actions in the "Ecological Intervention Areas" while ensuring connectivity between "Ecological Conservation Areas".

LUIGI approach to mapping ecological corridors

The scope of the LUIGI project has been to identify ecological corridors that could favour the movement of medium-large forest mammal species between Ecological Conservation (SACA 1) areas.

Ecological Conservation (SACA 1) areas have been used as "core" areas to be connected to allow consistency and comparability with the Interreg Alpine Space Project AlpBionet 2030. These areas have a minimum size of 100 ha and have been identified considering the following variables: Altitude and Topography; Population; Land use; Environmental protection; Fragmentation. For more details on the methodology used by Alpbionet 2030, visit:
https://www.alpine-space.org/projects/alpbionet2030/en/project-results/wpt3

Medium-large forest mammals have been very often used as a focal species group for ecological connectivity assessments because the breadth of their movements makes them particularly susceptible to habitat loss and fragmentation, and because they can act as umbrella species for other animals with more limited habitat requirements (Carrao et al., 2020; de la Fuente et al., 2018; Garrutxaga et al. 2010, 2011, Beier 2008).

Ecological corridors were modelled and mapped taking in account of the **landscape resistance**, which represents the degree to which the landscape facilitates or impedes animal movement across different land uses. In this context, land use or landscape resistance is intended as the opposite of habitat suitability, meaning that, for example, forests have a low resistance to animal movement (1), while urban areas have the highest (1000). The resistance of the landscape to animal movement ranged from 1 to 1000 and has been determined mainly in relation to the naturalness of different land use and land cover classes, following Garrutxaga et al. 2010 and the latest EEA- ETC/ULS report (Carrao et al., 2020). Some deviations from the landscape resistance values indicated in the EEA report have been made in consideration of the high-resolution land cover map used in LUIGI (5 m) as compared the Corine Land cover map (100m) used in the assessments at the EU-wide scale. The high-resolution map enabled the consideration of smaller landscape features (roads, single buildings, hedgerows) and a more accurate representation of the small-structured alpine landscape. Moreover, any area with a slope steeper than 55° was scored as "1000" to consider extremely difficult and exposed terrain as an influencing factor on movement. The landscape resistance values used in the LUIGI project are the following:

Table 2 Resistance values used in the modelling of ecological corridors

Land use and land cover classes	Resistance to animal movement
Artificial surfaces, settlements, and motorways	1000
Open settlement area and green urban areas	100
Train tracks, and secondary and primary Roads	100
Tertiary and other Roads	80
Unpaved Roads and Tracks	15
Cultivated areas - Arable Land - Annual Crops	60
Permanent Crops	15
Vineyards and Orchards	60
Managed Grassland - Pastures -	30
Seminatural Grassland - Meadows	20
Broadleaf and/or Coniferous tree cover (density 10-30%)	5
Broadleaf and/or Coniferous tree cover (density > 30%)	1
Other tree cover in urban and agricultural settings (density >10%)	5
Green Linear Elements and Woody Features	5
Alpine and sub-alpine natural grassland	20
Moors and Heathland	5
Sclerophyllous vegetation	5
Beaches, dunes, sands	40
Bare rocks and rock debris	40
Sparsely vegetated land	40
Permanent snow-covered surfaces	40
Water bodies, peatbogs, and wetlands	100
River network	15
Riverbed > 10m width	100

Given the core areas and the landscape resistance values for the target animal species described above, the mapping of the ecological corridors was carried out using the freely available “Linkage Mapper” and “Circuitscape” toolboxes in ArcGIS (available at https://circuitscape.org/). These tools use electrical circuit theory to model the movement of animals between core areas throughout a continuous landscape characterized by a range of different resistance values, allowing to identify least-cost paths connecting Ecological Conservation Areas. Least-cost paths constitute the middle of ecological corridors, and corridor width was set to 2 km of cost-weighted distance units. These models require a shapefile with the core areas that should be connected, a raster with the landscape resistance to animal movement, and a set of values specified by the user.

The **outputs** of the analysis conducted using the suite of tools in the Circuitscape and Linkage Mapper toolboxes comprised of:

- Current connectivity (raster)
  Cost-weighted distances represent the effort it takes for an animal to move away from each core area. This is a function of both the distance travelled from each core area and of the resistance

values of all the pixels encountered up to that point. Areas close to core areas, with low resistance values, have lower cost-weighted distances values (Low values = better animal movement).

- Least-cost paths (shapefile)
  The lines that connect each pair of core areas in the most efficient way, encountering the least landscape resistance.

- Ecological corridors and pinchpoints (raster)
  Ecological corridors are the areas closer to the least-cost paths. Pinchpoints represent narrow sections or bottlenecks within the corridor that are particularly critical for the flow of animal movement within each corridor. High values represent higher flow and higher importance.

- Core areas centrality (shapefile)
  Attribute of the core areas shapefile (i.e., Ecological Conservation Area or SACA1), describing the centrality of each core area in the network. Higher values imply higher centrality and importance.

- Barriers (raster)
  Areas that affect the quality and location of ecological corridors.

Technical details in the mapping of ecological corridors

The extent of the area analysed consists of the **LUIGI pilot regions** and a 10 km buffer around their administrative boundary (40 km in the case of the Metropolitan city of Milan).

Neighbouring LUIGI pilot regions were analysed together to map transboundary ecological corridors. The following regions have been analysed:

1- The province of South Tyrol (IT) and the canton of Grisons (CH)
2- The Metropolitan City of Milan (IT)
3- The Metropolitan city of Turin (IT) and the Departments of Isère, Savoie and Haute-Savoie (FR)
4- The Metropolitan city of Munich (DE) and the Central Area of Salzburg (AT)
5- Südburgenland (AT)
6- Goriška Region (SI)

Core areas were the shapefiles of the outlines of the Ecological Conservation Areas (i.e., SACA1) included in the extent of the mapping effort (pilot regions+ buffer). Water bodies were excluded.

Resistance rasters were obtained with the following steps:

- Clipping the region of interest (pilot region + buffer)
- Reclassifying the 5m land use map developed by Eurac Research using the landscape resistance values in Table 2.
- Reclassifying areas with a slope > 55° to the value of 1000. A 25 m Digital Elevation Model was used for this step.
- Resampling the landscape resistance map to 20m using the “AGGREGATE” function and the mean value method.

Using the Linkage Pathway tool

This tool calculates *cost-weighted distances* (raster file) between core areas, allowing to identify the *least cost pathways* (vectors in a shapefile) connecting core areas (i.e., the linear paths that accumulate least weight passing through different land use resistances on the way to reach the next core area). This is the step which takes the longest time to compute, and which is greatly affected by the size of the area to analyse, the cell size of the landscape resistance raster, and the number of core areas to connect. Settings defined by the user can help to narrow down the number of least cost paths and the area to analyse and compute, improving calculations time. Once least cost paths have been identified, the tool calculates the *mosaicked corridors* (raster file) of the whole region, where the centre of the corridors are the least cost paths. Getting further away from the least cost paths increases the resistance encountered and decreases the suitability of the corridor. The width of the corridors can be decided by the user in a later step. In LUIGI, we set it to 2 km.

For more details on how to run the tool, please follow the user guides provided within the Linkage Mapper Toolbox. ArcGIS 10.0 (or higher) with a Spatial Analyst extension is required to run this tool.

Here we list the values and options used in our analysis:

Network Adjacency Model: 'Cost-Weighted & Euclidean',
Drop Corridors that Intersect Core Areas: 'true',
Maximum Number of Connected nearest neighbours: '5',
Nearest Neighbour Measurement unit: 'Cost-Weighted',
Connect Neighbouring Constellations: 'true',
Truncate Corridors: '400000' (400 km),
Bounding Circles Buffer Distance: '20000' (20km),
Maximum Cost-Weighted Corridor Distance: '100000' (100 km),
Maximum Euclidean Corridor Distance: '50000' (50km)

(McRae, B.H. and D.M. Kavanagh. 2011. Linkage Mapper Connectivity Analysis Software. The Nature Conservancy, Seattle WA. Available at: http://www.circuitscape.org/linkagemapper.)

Using the Centrality Mapper

This tool allows to prioritize the links calculated in the previous step, identifying the core areas and the least cost paths that are more central and critical to the network. This step does not take much time to compute. Results are added as attributes of the least cost paths and core areas shapefiles.

For more details on how to run the tool, please follow the user guides provided within the Linkage Mapper Toolbox. ArcGIS 10.0 (or higher) with a Spatial Analyst extension is required to run this tool.

(McRae, B.H. 2012. Centrality Mapper Connectivity Analysis Software. The Nature Conservancy, Seattle WA. Available at: http://www.circuitscape.org/linkagemapper .)

Using the Pinchpoint Mapper

This tool uses the corridors mapped with Linkage Mapper and identifies pinch points, or bottlenecks within the corridors (i.e., constrictions representing narrower sections of the corridors where a higher flow is expected). Corridors have been set to have a maximum width of 2 km (in cost-weighted distances, meaning that corridors in forest areas are wider, and corridors in anthropized settings are narrower.)

For more details on how to run the tool, please follow the user guides provided within the Linkage Mapper Toolbox. ArcGIS 10.0 (or higher) with a Spatial Analyst extension is required to run this tool.

Here we list the values and options used in our analysis:

Corridor Width: ‘2000’,
Square resistance values?: 'false',
Calculate adjacent pair pinchpoints using Circuitscape: 'true',
Calculate raster centrality: ‘false’,
Circuitscape mode for raster centrality calculations: 'All-to-one'

(McRae, B.H. 2012. Pinchpoint Mapper Connectivity Analysis Software. The Nature Conservancy, Seattle WA. Available at: http://www.circuitscape.org/linkagemapper .)

Using the Barrier Mapper

This tool allows to detect important barriers that affect the quality or location of the corridors mapped using Linkage Pathway.

For more details on how to run the tool, please follow the user guides provided within the Linkage Mapper Toolbox. ArcGIS 10.0 (or higher) with a Spatial Analyst extension is required to run this tool.

Here we list the values and options used in our analysis:

Minimum detection radius: ‘200’,
Maximum detection radius: ‘600’,
Radius step value: ‘200’,
Method for combining across multiple core area pairs: ‘Maximum’
Write barrier rasters for each search radius: ‘false’,
Calculate percent improvement scores relative to corridor LCD: ‘true’

(McRae, B.H. 2012. Barrier Mapper Connectivity Analysis Software. The Nature Conservancy, Seattle WA. Available at: http://www.circuitscape.org/linkagemapper .)

Mapping ecosystem multifunctionality in the LUIGI pilot regions

Terrestrial ecosystems support many ecosystem processes that give rise to multiple ecosystem functions and services. Such services can support us in addressing societal challenges, supporting food production, climate change mitigation and adaptation, mitigating natural hazards, and promoting human well-being. In the LUIGI project, 11 ecosystem services indicators were spatially-explicitly modelled and mapped at high resolution (10-25 m) to identify areas supporting high ecosystem services-based multifunctionality. The assessed ecosystem services build on the Common International Classification of Ecosystem Services (CICES v.5.1) and describe the potential supply of ecosystem services across the project pilot regions. Ecosystem services were selected and mapped according to their relevance for the Alpine Space and the availability of spatial data at the right resolution to model them. To calculate ecosystem services-based multifunctionality, we modelled and mapped the following 11 ecosystem services:

- **Provisioning ecosystem services**: water provision, crop potential, fodder provision, timber provision
- **Regulation and maintenance ecosystem services**: natural hazard mitigation, pollination potential, water flow regulation, water nitrogen filtration, carbon sequestration
- **Cultural ecosystem services**: outdoor recreation potential, landscape aesthetics

LUIGI approach to mapping ecosystem service-based multifunctionality

Ecosystem services-based multifunctionality was assessed separately for different land use groups (agricultural landscapes, forests, urban areas, and “open” spaces at high elevations). Such land use groups reflect different levels of anthropization, and the different management, regulations and practices put in place by different sectors of public administrations. Given that the role of forests as multifunctional land use systems is already widely acknowledged (European Commission, 2013), we decided to apply a more practice-oriented approach to give more precise indications to practitioners working in different land use groups. This multifunctionality indicator indeed aims to highlight the most multifunctional areas within each land use group (i.e., within urban areas, forest areas, agricultural landscapes, open areas above the tree-line).

This approach relies on the assumption that within each land use group there are areas that are outperforming others in terms of ecosystem service provision and are therefore more multifunctional than others. **Our measure of multifunctionality therefore highlights the *relatively* possible ES provision that can be expected from each ecosystem/land use group**. Hence, specific standardization and normalization of the 11 mapped ES indicators is necessary for each land use group. Multifunctionality was calculated as the average ecosystem services value within each land use group. A final composite map was then created by merging the four groups to identify area-wide patterns of multifunctionality. Areas displaying values falling into the top 10% of the multifunctionality values were considered to be highly multifunctional.

Multifunctionality was calculated including all of the LUIGI pilot regions together, making **the ecosystem services-based multifunctionality values comparable across pilot regions**. Multifunctionality values are therefore in relation to the whole extent of the LUIGI pilot regions: some pilot regions have an average multifunctionality value which can be higher or lower that the LUIGI pilot regions’ average.

Methodological overview of the ecosystem services-based multifunctionality indicator

Indicator description: The ecosystem services-based multifunctionality of the areas within the pilot regions of the Interreg Alpine Space project LUIGI represents an index value calculated out of the average of 11 standardized ecosystem service indicators in urban areas, forest areas, agricultural landscapes, open areas above the tree-line.

Tools and software used: ArcGIS 10.8

Input data: Corine Landcover v2018, 11 ecosystem service indicators mapped at 10-25 m resolutions

Methodological steps:

1) Land use group classification: we used the Corine landcover to delineate *urban areas* (Corine classes 1.1-1.4), *forest areas* (Corine classes 3.1), *agricultural areas* (Corine classes 2.1-2.4) and *open areas* (3.2-5.2). The broader, landscape view given by the medium spatial resolution of the Corine land cover allowed to include also smaller ecosystems and landscape elements that at higher spatial resolution would not have been included (e.g., hedgerows and small woods in agricultural landscapes, forest roads etc).
2) Standardization and normalization of 11 ES for the pixels located within each land use group. This is done separately for each land use group. The following formula is used to account for varying ES provision potentials and to exclude statistical outliers from the standardization process.

$$Con(ES_i < (x_i + 3*\sigma_i), ES_i/(xi+(3*\sigma_i)\ )*100,100)$$

(ES_i= ecosystem service value, x_i=average, σ_i = standard deviation)

was used for standardization using a GIS raster calculator (with the exception where $x_i + (3*\sigma_i)$ is higher than the maximum value of the ES distribution. In this case, the maximum value of the raster distribution was used instead of $x_i + (3*\sigma_i)$). (N.B. *Con* in raster calculator is the same as an *IF-ELSE* statement).
3) The mean value of the 11 re-standardized ES is calculated for each pixel. This is done separately for each land use group.
4) Mosaic each land use group ecosystem service mean into a single **multifunctionality map.**
5) Areas displaying values falling into the top 10% of the multifunctionality values were considered to be highly multifunctional.

Main references:

- Hölting, L., Beckmann, M., Volk, M., & Cord, A. F. (2019a). Multifunctionality assessments – More than assessing multiple ecosystem functions and services? A quantitative literature review. Ecological Indicators, 103, 226–235. https://doi.org/10.1016/j.ecolind.2019.04.009
- Stürck, J., & Verburg, P. H. (2017). Multifunctionality at what scale? A landscape multifunctionality assessment for the European Union under conditions of land use change. Landscape Ecology, 32 (3), 481–500. https://doi.org/10.1007/s10980-016-0459-6

Ecosystem services indicators included in the multifunctionality assessment

The ecosystem services indicators have been modelled mainly referring to and applying methodologies present in the literature that, in some cases, were adapted to the purpose and resolution of the assessment. The mapping procedure involved the use of a high-resolution land use map, topographic variables such us elevation, slope and aspect, and climatic variables such as Growing Degree Days (GDD), mean annual temperature, precipitation, and solar radiation. Given the lack of a European-wide database on organic agriculture or forestry practices, croplands are assumed be managed intensively, while forests are assumed to be managed sustainably.

To allow consistency and alignment with previous European projects, the ecosystem services mapping procedure built on the results obtained in the Interreg Alpine Space project AlpES. We however acknowledge that other methodologies and approaches can be suitable to map individual ecosystem services, according to the data and technical expertise available.

We here describe the assumptions and variables used in modelling and mapping the above-mentioned ecosystem services indicators, which were used to assess multifunctionality in the LUIGI project.

Water provision

ES category: provisioning

This indicator estimates the annual local water provision for general use. It is composed of a water budget (Precipitation – Evapotranspiration by plants) combined with the influence of the soil and landcover on the infiltration rate of precipitation. It estimates ground and soil water recharge at pixel level and excludes surface runoff.

Main references:

- Nistor, M.M. & Porumb-Ghiurco, Gc. (2015). How to compute the land cover evapotranspiration at the regional scale? A spatial approach of Emilia-Romagna region, GEOREVIEW(25) https://doi:10.4316/GEOREVIEW.2015.25.1.268
- Rahardjo, H., Satyanaga, A., & Leong, E. (2013). Effects of flux boundary conditions on pore-water pressure distribution in slope. Engineering Geology(165), 133-142, https://doi.org/10.1016/j.enggeo.2012.03.017
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Crop potential

ES category: provisioning

This indicator estimated the potential to grow crops based on climatic conditions (described in Growing Degree Days, which show daily temperature accumulations), water availability (Precipitation – Evapotranspiration), and topography (slopes steeper than 26.5° where excluded). Soil was not considered as a limiting factor since for agriculture some kind of soil treatment and preparation is always necessary and possible.

Main reference:

- Bock, M., Gasser, P. Y., Pettapiece, W. W., Brierley, A. J., Bootsma, A., Schut, P., …& Smith, C. A. (2018). The land suitability rating system is a spatial planning tool to assess crop suitability in Canada. *Frontiers in Environmental Science*(6), 77. https://doi.org/10.3389/fenvs.2018.00077

Timber provision

ES category: provisioning

Sustainable forest management is largely limited to the regrowth rate in order to keep forest inventory stable. Hence, this indicator reflects the net annual increment of biomass in Alpine forests. Forest biomass increment is derived from the extrapolation of MODIS satellite Gross Primary Productivity data, using the base of forest typology, altitude, and climatic macro-area factors from the Swiss National Forest Inventory. The indicator is based on the results of the AlpES project.

Main reference:

- Busetto, L., Barredo, J. & San-Miguel-Ayanz, J. (2014). Developing a spatially-explicit pan-European dataset of forest biomass increment. *Environmental Science*

Fodder provision

ES category: provisioning

This indicator estimates annual grassland biomass (fodder) production in intensively used, moderately used and extensively used grassland. It is comprised of two main models. The first part assesses the optimal yield according to the length of the growing season, the respective growth functions, and the specific land use types. The second part refines the biomass productivity according to region-specific precipitation patterns and local small-scale topographic conditions, in order to provide more reliable local yield estimates. The indicator is based on the results of the AlpES project.

Main reference:

- Jäger, H., Peratoner, G., Tappeiner, U., & Tasser, E. (2020). Grassland biomass balance in the European Alps: current and future ecosystem service perspectives. *Ecosystem Services*, 45(101163). https://doi.org/10.1016/j.ecoser.2020.101163

Carbon sequestration

ES category: regulating and maintenance

This indicator represents the annual rate of CO2 sequestration by the current landcover. This value is calculated using a constant converting above- and below-ground biomass increment in forests and grasslands into the tonnes of carbon of CO2 being sequestered per year. Biomass increment in other land cover types was estimated with proxies or interpolations from land uses in the surrounding areas. The indicator is based on the results of the AlpES project.

Main references:

- Busetto, L., Barredo, J. & San-Miguel-Ayanz, J. (2014). Developing a spatially-explicit pan-European dataset of forest biomass increment. *Environmental Science*

- IPCC (2006), Aalde H., Gonzalez P., Gytarsky M., Krug T., Kurz W.A., Ogle S., Raison J., Schoene D., Ravindranath N.H. et al. IPCC Guidelines for national greenhouse gas inventories, prepared by the national greenhouse gas inventories program, Vol. 4, Ch. 2-4, Forest Land

Water nitrogen filtration

ES category: regulating and maintenance

This indicator model* represents the amount of nitrogen contained in water run-off that is potentially filtered by ecosystems. Sources of nutrients across the landscape, also called nutrient loads, are determined from a land use/land cover (LULC) map and associated loading rates. The model uses a mass balance approach, which describes the movement of a mass of nutrients through space. Each pixel is characterized by its nutrient load, and its nutrient delivery ratio, which is a function of the upslope area and downslope flow path (in particular the retention efficiencies of LULC types on the downslope flow path). *the indicator was calculated with the InVEST "Nutrient Delivery Ratio (NDR)" model

Main reference: http://releases.naturalcapitalproject.org/invest-userguide/latest/ndr.html

Natural Hazard Mitigation (NHM)

ES category: regulating and maintenance

Natural Hazard Mitigation merges the results of Natural hazard mitigation 1 + 2 by calculating the average value between the two following layers:

NHM1: Soil erosion prevention

This indicator estimates the capacity of vegetation to prevent soil erosion. Using the Revised Universal Soil Loss Equation, soil erosion rates are calculated based on *rainfall erosivity, soil erodibility*, and *topography*. Soil retention is estimated based on proxy values of *Vegetation cover* and *soil management practice (e.g., terracing)*.

Main references:

- Guerra, Carlos A., Maes, J. Geijzendorffer, I. Metzger, M.J. (2016). An assessment of soil erosion prevention by vegetation in Mediterranean Europe: Current trends of ecosystem service provision. *Ecological Indicators*(60), 213-222. https://doi.org/10.1016/j.ecolind.2015.06.043
- Fu, B., Liu, Y. Lü, Y., He, C. Zeng, Y., Wu, B., (2011). Assessing the soil erosion control service of ecosystems change in the Loess Plateau of China. *Ecological Complexity*(8), Issue 4, 284-293. https://doi.org/10.1016/j.ecocom.2011.07.003.

NHM2: Forest protection

This indicator delineates areas where forests contribute to the mitigation of natural hazards and the protection of human assets from them. At the Alpine-wide scale, this has been done by combining separate regional models for avalanches, rock-falls, landslides and water channels. These models were based on the presence of bare rock or snow-cover areas on steep slopes (in release zones), on the topography, slope length, and land cover roughness (in transition zones), on the presence of steep terrain around water channels, and on the distribution of forests. The model was developed within the AlpES project.

Main references:

- Bauerhansl, C., Berger, F., Dorren, L., Duc, P., Ginzler, C., Kleemayr, K., ... & Seeback, L. (2010). Development of harmonized indicators and estimation procedures for forests with protective functions against natural hazards in the alpine space (PROALP). Luxembourg: Office for Official Publications of the European Communities, JRC Scientific and Technical Report, 56151, 181.
- Berger, F., Larcher, V., Simoni, S., Pasquazzo, R., Strada, C., Zampedri, G., (2012). PARAmount Project WP6 guidelines - Rockfall and Forecast systems.
- Gruber, S., Huggel, C., Pike, R. (2008). Modelling mass movements and landslide susceptibility. In: Hengl, T; Reuter, H I. Geomorphometry. Amsterdam, 527-550.

Water flow regulation

ES category: regulating and maintenance

This indicator model* calculates the runoff reduction, i.e., the amount of runoff retained per pixel compared to the storm volume. Runoff retention is calculated based on land use type and soil characteristics with the curve number method, which estimates direct runoff or infiltration from rainfall excess. *the indicator was calculated with the InVEST "Urban Flood Risk Mitigation" model

Main reference: https://naturalcapitalproject.stanford.edu/software/invest

Pollination potential

ES category: regulating and maintenance

The methodology used focuses on wild bees as key animal pollinators. The indicator describes the relative capacity of ecosystems to support pollination and is based on the assumption that different habitats offer varying floral resources and nesting opportunities. The model also accounts for the influence of temperature and solar irradiance on the activity of insects. In addition, given that pollination services decrease by increasing the distance from natural and semi-natural areas, a distance decay function is applied. The methodology used was based on ESTIMAP: Ecosystem Service Mapping at European Scale.

Main references:

- https://publications.jrc.ec.europa.eu/repository/handle/JRC87585
- Zulian et al. (2013). Linking Land Cover Data and Crop Yields for Mapping and Assessment of Pollination Services in Europe. Land(2), 472-492. https://doi:10.3390/land2030472

Landscape aesthetics

ES category: cultural

This indicator describes the characteristics of landscapes that enable aesthetic experiences. The model of the landscape aesthetic value is composed of two factors:

- the visibility of an area (i.e. pixel) as observed from the rest of the region, from built-up areas and from locations where Flickr photos are taken.
- the objective aesthetic beauty of the area, modelled using proxy values for landcover types and applying focal averages within 500 meters since landscape is always perceived as a location together with its surroundings.

Main reference:

- Schirpke, U., Zoderer, B. M., Tappeiner, U., Tasser, E. (2021). Effects of past landscape changes on aesthetic landscape values in the European Alps. Landscape and urban planning(212). https://doi.org/10.1016/j.landurbplan.2021.104109

Outdoor recreation potential

ES category: cultural

This indicator was calculated by assessing the capacity of ecosystems to support nature-based recreation opportunities and is the combination of two models: model *a*) focus on daily outdoor recreation near urban areas and model *b*) assesses the general potential for mountain outdoor recreation during weekends and trips.

a) The model creates a Recreation Opportunity Spectrum (ROS) by cross-tabulating two thematic maps: a Recreation Potential (RP) map (based on land use, natural features, and size of urban parks) and a Proximity map (based on the presence of access facilities such as roads or bus stops, and user facilities such as mountain huts or benches). The methodology is based on ESTIMAP: Mapping Ecosystem Services at European Scale.

b) The model was developed within the AlpES project to map Outdoor Recreation supply, which was based on the recreational value of protected areas, degree of human impact, distance to water, diversity of cover types, terrain roughness, and density of mountain peaks.

Main reference:

- Cortinovis, C., Zulian, G. and Geneletti, D., 2018. Assessing nature-based recreation to support urban green infrastructure planning in Trento (Italy). Land, 7(4), p.112.
- Schirpke, U., Meisch, C., Marsoner, T., & Tappeiner, U. (2018a). Revealing spatial and temporal patterns of outdoor recreation in the European Alps and their surroundings. Ecosystem Services(31), 336–350. https://doi.org/10.1016/j.ecoser.2017.11.017

Links to useful data sources

- Precipitation, radiation and temperature parameters – Worldclim dataset: https://www.worldclim.org/data/worldclim21.html
- Landcover map - developed by Eurac Research, unpublished
- Growing Degree Days – University of Alberta: https://sites.ualberta.ca/~ahamann/data/climateeu.html
- Forest HRL – Copernicus: https://land.copernicus.eu/pan-european/high-resolution-layers/forests
- Digital Elevation Model – Copernicus: https://land.copernicus.eu/imagery-in-situ/eu-dem/eu-dem-v1-0-and-derived-products
- Clay, Silt and Sand soil content, Soil Organic Carbon stock – Soilgrids (250 m resolution): https://soilgrids.org/
- Landcover nesting suitability and floral availability scores - Joint Research Center: https://publications.jrc.ec.europa.eu/repository/bitstream/JRC87585/lb-na-26474-en-n.pdf
- Flickr images-points: https://www.flickr.com
- Green urban areas, cycle paths – OpenStreetMap: https://www.openstreetmap.org