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**Green infrastructure planning based on ecosystem services multicriteria evaluation: the case of the metropolitan wine landscapes of Bordeaux**

Giovanna Calia,[1,2] Vittorio Serra,[1,*] Antonio Ledda,[1] Andrea De Montis[1,2]

[1]Department of Agricultural Sciences, University of Sassari; [2]Department of Civil and Environmental Engineering and Architecture, University of Cagliari, Italy

**Correspondence**: Vittorio Serra, Department of Agricultural Sciences, University of Sassari, viale Italia 39A, 07100 Sassari, Italy. E-mail: vserra@uniss.it

**Key words:** Green infrastructure planning, ecosystem services, multi-criteria analysis.

**Abstract**
Excessive anthropogenic activities affect landscape patterns and trigger a decrease of natural capital and the level of quality of life. Green infrastructures (GIs) are commonly accepted by scholars as solutions for restoring degraded areas and providing a variety of ecosystem services (ESs). The other way around, the capacity to deliver ESs can be assumed as a relevant starting point for GIs analysis and planning. The assessment of ESs needs extensive investigation and applications, to provide planners, policy makers, and institutional stakeholders with an adequate evaluation tool. The multi-facet nature of ESs assessment implies the use of complex tools able to consider many concerns. In this regard, multicriteria analysis (MCA) is a very popular tool due to its capacity to intertwine a variety of issues in a rigorous way and to support participatory and transparent decision making in the public domain. In this study, we aim at contributing to the integration of GI design into spatial planning starting from the assessment of the net benefit delivered to local society by a GI in the metropolitan area of Bordeaux (France). We assessed the net benefit by confronting the ESs deliverable by the GI and the cost sustained for its construction and maintenance. We applied an MCA-based method to the selection of the most efficient alternative out of three GI paths. We demonstrate that our method is useful for the assessment of cultural and regulating ESs, comparing the GI design alternatives, and considering the preference model of the stakeholders within GI planning and design.

## Introduction

The world population is constantly increasing (United Nations and Department of Economic and Social Affairs, Population Division 2019), and the use of soil is always more leaning towards urbanization and intensive agriculture. This leads to the decrease of natural capital (Ghofrani, Sposito, and Faggian 2017) including all natural terrestrial and aquatic resources and atmosphere, able to provide services (Moyzeová 2018). These excessive anthropic activities have changed the pattern of landscape (Senes et al., 2020), sparking decline of green areas in urban and peri-urban zones, loss of services provided by ecosystems, with consequently lowering of people's well-being (Ghofrani, Sposito, and Faggian 2017). Restoring of degraded green areas and re-naturalizing processes of abandoned natural areas could be achieved by implementation of green infrastructures (GIs) (European Commission 2013). GIs are related to nature-based solutions (Andreucci, Russo, and Olszewska-Guizzo 2019; Senes et al., 2021) with the main feature of multifunctionality, as well as protect and conserve biodiversity and habitats (European Commission 2013). GIs can be realised at different scales, based on ecosystem services that can be provided (Langemeyer et al. 2020). GIs adopt the same structure of ecological networks, but can supply a large range of services, for example recreative, healthy areas, regulating of micro-climate and pollution, etc. (Magaudda et al. 2020; Andreucci, Russo, and Olszewska-Guizzo 2019; Matthews, Lo, and Byrne 2015). Hence, GIs planning goes through ESs assessment, to achieve a successful design and favour inclusion of GIs and ESs in spatial planning processes, to date not yet effectively diffused (García et al. 2020b; de Manuel et al. 2021). Assessment of ESs is a field that needs more extensive investigation and applications, in order to promote appropriate evaluation tools for planner, policy makers and institutional stakeholders involved in GIs planning and design (Langemeyer et al. 2016). The multi-facet nature of ESs assessment implies the use of complex tools able to consider many concerns. In this respect, multicriteria analysis (MCA) is a very popular tool for its capacity to intertwine a variety of issues in a rigorous way and to support participatory and transparent decision making in the public domain.

In this study, we aim at contributing to the integration of GI design into spatial planning starting from the evaluation of the net benefit delivered to local society by a GI in the metropolitan area of Bordeaux, France. We assess the net benefit by confronting the ESs deliverable by the GI and the cost sustained for its construction and maintenance. We propose a MCA-based method able to combine the assessment of some regulatory and cultural ESs and costs. We apply the method to the

selection of the most efficient alternative out of three GI paths.
The argument of this paper revolves around three research questions (RQs). RQ1 attains the nature and rationale of the methodological approach useful for supporting the design of the most efficient GI. RQ2 concerns the ability of the method to consider the balance between the delivery of ecosystem services and the construction and maintenance costs. Finally, RQ3 regards the exportability of the method to other decisional and planning contexts in the public domains.
This paper is organized as follows. In the next section, we review the scientific cornerstones of this study attaining GI analysis and planning, ES definition and assessment, and MCA evaluation of ESs. In the third, fourth, and fifth sections (Materials and methods) we respectively illustrate the MCA-based method adopted, describe the case study, and the data set adopted. In the sixth section, we apply the method to the case study of the metropolitan area of Bordeaux and present the results. In the seventh and eighth sections, we discuss the findings and present the final remarks of our study.

**State of the art summary**

This paper is based on three cornerstones: GI analysis and planning, ESs assessment, and MCA. Each concept has been reviewed in the literature, as reported below.
Green infrastructures (GI) arise as possible solutions for counteracting the decline of biodiversity, maintaining landscapes and habitats, and increasing the resilience of communities. GIs are a network of natural e seminatural areas, planned to provide ecosystem services or benefits for people, and safeguarding biodiversity, in urban and rural contexts. Despite European the Commission promoted the adoption of GIs since 2013, to date the guide to planning and design of GIs is still under study (Ronchi, Arcidiacono, and Pogliani 2020). The inclusion of GIs in spatial planning processes is one of challenges of spatial planners (Matthews, Lo, and Byrne 2015): in different European region, the integration of GIs in plans/institutional documents is still in its infancy (De Montis, Ledda, and Calia 2021; Di Marino et al. 2019; Grădinaru and Hersperger 2019; Ledda et al. 2023). In this respect, local spatial planning is a crucial process to favour GIs diffusion at the large scale, particularly the adoption of specific policies, measures and guidelines (Irga et al. 2017). Planners have approached GI design in a variety of ways. For example, Li et al. proposed a quantitative evaluation method to identify priority areas, by using quantitative evaluation method based on the use of appropriate indicators (Li, Uyttenhove, and Van Eetvelde 2020). Langemeyer et al. (2020) based their planning method on spatial screening to identify priority areas of future green roofs network in the urban area of Barcelona (Spain). Other authors focused on spatial allocation of multiple restoration measures at a regional scale across three aquatic ecosystems in fresh, coastal, and marine waters (Barbosa et al. 2019). However, various factors affect the diffusion of GIs, as stakeholders' opinions (Reu Junqueira, Serrao-Neumann, and White 2022), financial resources (Fondazione per lo sviluppo sostenibile and Green City Network 2018), mapping of green areas (González-García et al. 2022), use of indicators (Pakzad and Osmond 2016; Pakzad, Osmond, and Corkery 2017) etc. De Montis et al. (2021) define a method to draft GIs design guidelines, as a tool including GIs in spatial planning and decision processes. The tool is based on the following key steps: study of local policies, context analysis and stakeholders' involvement. In general, the authors agree that participative planning of GIs is one of the most effective tool for their adoption and diffusion (Kušar 2019).
Secondly, ecosystems support humans' life and provide services -i.e., ecosystem services (ES)- to their well-being (La Notte 2017). There is no unique definition or meaning of ES. Fisher, Turner, and Morling (2009) found some interesting meanings: i) conditions in which ecosystems support human life, ii) the benefits obtained by people accessing the functions of the ecosystems, iii) ecological components able to provide benefits. According to Common International Classification of Ecosystem Services (CICES) and Haines-Young, and Potschin (2018), ESs are grouped into three main categories associated to the: provision (all nutritional, non-nutritional material and energetic outputs from living systems and abiotic outputs), regulation and maintenance (all the ways in which

living organisms can mediate or moderate the environment), and culture (all the non-material outputs of ecosystems that affect physical and mental states of people). Fisher, Turner, and Morling (2009) stressed the need to assess ES delivery and measure the variation of ES provision in space and time. The assessment of ESs could provide an important tool to support GI planning (Zhang and Muñoz Ramírez 2019). The inclusion of ESs assessment and mapping in spatial planning as a base for decision making is still a challenging issue (García et al. 2020b). They claim that ESs assessment is a priority for spatial planning of green areas, including the design of GIs (Ronchi, Arcidiacono, and Pogliani 2020). The assessment of ESs includes the observation of ecological aspects as a whole, but also of human-centred phenomena related to their final use (La Notte 2017). Different approaches have been used for assessing ESs. For example, Zhang and Muñoz Ramírez (2019) used a set of indicators able to gauge and map the spatial pattern of ESs provision by GIS-based advanced spatial analysis of land use data. García et al. (2020b) focused on the assessment of ESs classified in the three types proposed by CICES by attributing a weight to the corresponding land cover classes. de Manuel et al. (2021) apply an indicator-based method for assessing the spatial efficiency of the urban neighbourhoods of Bilbao, in terms of mismatch between ES supply and demand.
As a third issue, multi-criteria analysis (MCA) is a multi-facet method supporting the evaluation of a set of alternatives or actions with respect to many points of view measured by criteria, and improving the reliability and transparency of the analysis (Yang et al. 2021). In this respect, MCA includes the attribution of weights -i.e., indexes of the level of mutual importance- to the criteria (Langemeyer et al. 2016). MCA is an ideal candidate tool for ES evaluation, even though the applications are still relatively rare (Li, Uyttenhove, and Van Eetvelde 2020; Langemeyer et al. 2020; García et al. 2020a). Langemeyer et al. (2016) review MCA-based approaches to ES assessment and focus on the opportunity of integrating a variety of issues: ecological, social and economic values, stakeholder preferences, spatial locations, etc. Li, Uyttenhove, and Van Eetvelde (2020) apply MCA to assess ES, with respect to the improvement of resilience against urban surface water flood risk at a local scale. They classify areas in three classes with a different measure of risk, by combining information connected to five indicators and useful for detecting priority areas in a future GIs. Langemeyer et al. (2020) applied a MCA-based method to measure the capacity of green roofs to deliver ESs. They assessed five alternatives and mapped the most efficient areas to be included in a GI network including green roofs. García et al. (2020a) used MCA for mapping ESs provision and multifunctional areas classified according to size and compactness, land use or their proximity to other elements of the GIs.

## Materials and methods

The starting point of the method selected is the need to assess the efficiency of a certain GI alternative path. The efficiency can be measured by considering the net benefit associated to each path. So, a major tool is cost benefit analysis: a traditional tool adopted in environmental and landscape planning for budgeting public infrastructures (Escobedo, Kroeger, and Wagner 2011). In our case, the GI is meant as a common place accessible for free to any citizen, city user, tourist, etc. For this kind of public goods, the evaluation of the cost is relatively straightforward, as it implies the measurement of the cost of the activities involved during GI construction and management. By contrast, the assessment of the benefits usually implies finer modeling and calculation. In this case, the benefits can be modelled as regulatory and cultural ESs. Regulatory ESs are referred to the sequestration of carbon dioxide synthetized for vegetal biomass production, which belongs to the class “regulation of chemical composition of atmosphere”, code 2.2.6.1 of CICES V5 guide (Common International Classification of Ecosystem Services (CICES), Haines-Young, and Potschin 2018). Cultural ESs include walking, discovering cultural heritage trough vineyards, landscape conservation, sustainable viticultural, etc., belonging to the groups concerning “Physical and experiential interactions with natural environment” (3.1.1.1) and “Intellectual and representative interactions with natural environment” (3.1.2.1 and 3.1.2.3) (Common International Classification

of Ecosystem Services (CICES), Haines-Young, and Potschin 2018). As in this study a specific assessment of each ES is difficult in terms of lack of data, human and financial resources, and time, we focused on these specific ESs. We aim at providing planners and policy makers with a theoretical and practical approach to valorize the urban wine landscape as part of cultural heritage. Furthermore, we would like to point out the relevance of GIs as climate change adaptation measures. We are aware of the limitation of this assessment, which can however provide some design suggestions that can be replicated in other geographical-cultural contexts.
The combination tool selected for assessing the net benefit is MCA, whose cornerstones are: definition of the alternatives, selection of the criteria, attribution of scores to the alternatives, normalization of the scores, setting of the weights, obtaining final combined scores, and analysis of the sensitivity of the outcomes with respect to the input elements (in our case, the weights). In this case, we selected criteria as illustrated in Table 1.

**Table 1 Criteria selected for the evaluation of the alternatives.**

| Code | Description | Benefit/cost | Direction of preference | Type of ES associated (CICES) | Evaluation index | Variables involved | Units of measurement |
|---|---|---|---|---|---|---|---|
| CR1 | Access to GI for resident people | Benefit | Positive | Cultural and environmental | Accessibility | Population in GI-close buffers, distance | Number of residents, km |
| CR2 | Access to wetlands for GI users | Benefit | Positive | Environmental | Accessibility | Wetland surface area in close buffers, distance | Hectare (Ha), km |
| CR3 | Access to public buildings for GI users | Benefit | Positive | Cultural | Accessibility | Public buildings in close buffers, distance | Number of buildings, km |
| CR4 | Carbon sequestration in the short run | Benefit | Positive | Regulatory | $CO_2$ processed by young plants | Length, inter-distance, time, mass | Tons, hectare, year |
| CR5 | Carbon sequestration in the long run | Benefit | Positive | Regulatory | $CO_2$ processed by mature plants | Length, inter-distance, time, mass | Tons, hectare, year |
| CR6 | Cost of construction | Cost | Negative | - | Cost of plants, materials and services for GI building | Surface area, price | Square meter, Euro per square meter, Euro |
| CR7 | Cost of management | Cost | Negative | - | Cost of materials and services for GI refurbishing | Surface area, price, time | Square meter, Euro per square meter, Euro, year |

CR1-5 serve as proxies for the benefits a GI can provide and have a positive direction of preference (the higher the score the higher the utility), while CR6-7 as proxies of the costs of a GI and show a negative direction of preference (the higher the score the lower the utility). The first set of criteria is associated to ESs falling in different classes, according to CICES. CR1-3 are modelled by invoking the concept of accessibility (Geurs and van Wee, 2004) and CR4-5 the sequestration of carbon dioxide by vegetal biomass. We used accessibility as a proxy for the benefits connected to the corresponding ESs, since it well represents the spatially interested demographic basin and the endowment of natural resources and relevant buildings. In this respect, accessibility is an ideal measure of the opportunities related to people movement throughout destinations, where selected ESs are supplied (Ala-Hulkko et al. 2016, Cheng et al. 2019). According to Geurs and van Wee (2004), accessibility can be interpreted as a measure of the potential of opportunities "in zone *i* [with respect] to all other zones (*n*) in which smaller and/or more distant opportunities provide diminishing influences" (Geurs and van Wee, 2004, p. 133). It can be expressed by Equation 1:

$$A_i = \sum_{j=1}^{n} D_i e^{-\beta c_{ij}} \tag{1}$$

where "$A_i$ is a measure of accessibility in zone $i$ to all opportunities $D$ in zone $j$, $c_{ij}$ the costs of travel between $i$ and $j$, and $\beta$ the cost sensitivity parameter" (Geurs and van Wee, 2004, p. 133).

Inspired by Geurs and van Wee (2004), in this study the accessibility is calculated by applying Equation (2):

$$A = \sum_{1}^{n} A_i \tag{2}$$

where $A$ stands for total accessibility, $A_i$ for the accessibility of the $i$-th buffer, and $n$ is equal to the number of buffers. $A_i$ is calculated with Equation (3):

$$A_i = \sum_{1}^{m} O_j \, f(d_{ij}) \tag{3}$$

where $A_i$ stands for the accessibility of point $I$, $O_j$ for the potential of opportunity in $j$, while $d_{ij}$ for the Euclidean distance between $i$ and $j$. The opportunities are related to population, wetlands, public buildings, located within the four buffers (see below), with respect to the longitudinal axis of the GI's path; $f(d_{ij})$ stands for the movement friction and depends on the distance between the amenities and the GI. In this case, to model the friction of distance we adopt the following common equation obeying to the power law rule (Equation 4):

$$f_{power} = (d_{ij})^{-\alpha} \tag{4}$$

where $\alpha$ stands for a variable exponent depending on the resistance of $i$-th path (we used $\alpha = 2$). The four buffers used span 50, 100, 500 and 1000 m from the axis of the corridors, as explained in Figure 1.

Data concerning population density have been retrieved in geotiff format from WorldPop with a “resolution of 3 arc (approximately 100 m at the equator)” (Bondarenko et al., 2020). We converted cells (raster geotiff format) into points (vector shapefile format); so, the patterns of these points describes population density. Spatial data concerning population density (as well as wetlands, and public buildings) have been clipped through QGIS software for each buffer.

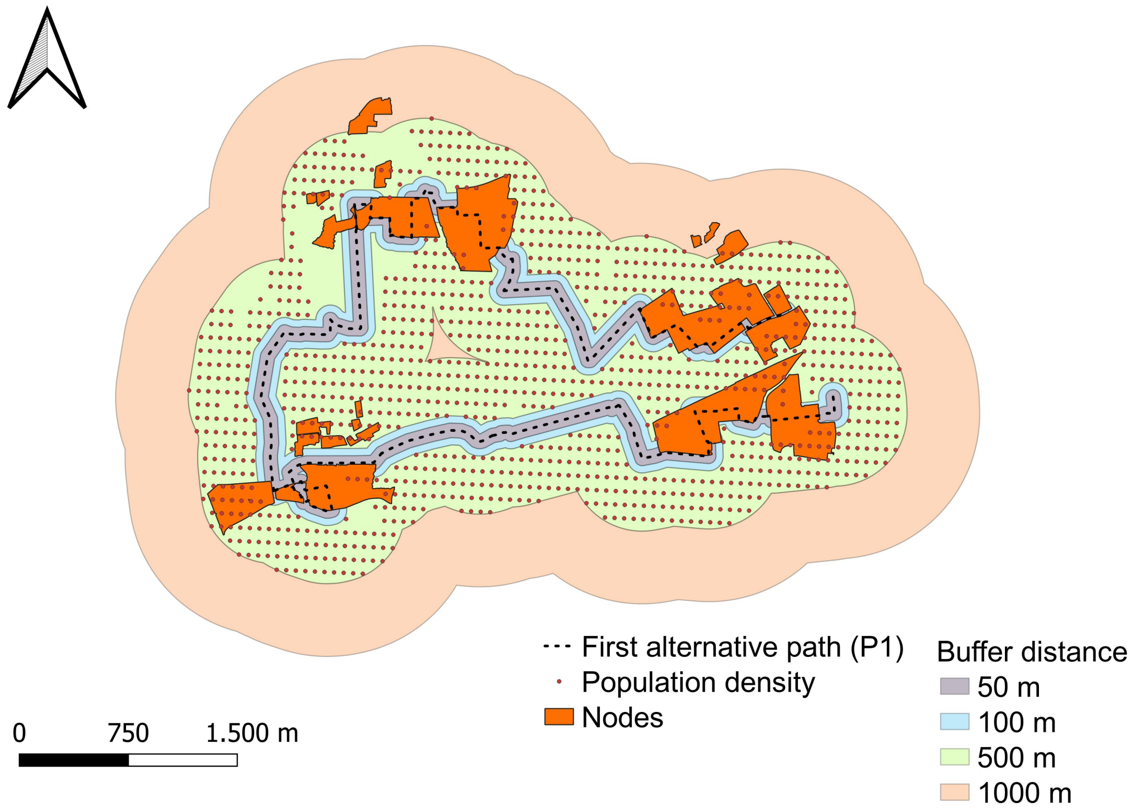


**Figure 1 Layout of the four buffers for the first alternative path.**

CR4-5 concern carbon dioxide sequestration (CDS) in the short and long run. CDS is assessed by considering the carbon dioxide - vegetal biomass conversion process characterizing young and mature plant growth.

As for CR6-7, we assess the cost of building and managing the GI, by estimating the total cost of the materials and activities required in each phase.

The scores are attributed to each alternative, according to the values released by the application of the criteria and their modeling. As score are expressed in different units of measurement, normalization is needed through the application of the min-max rule projecting each figure to the ratio between the divide from the minimum and the range of the variable. Other rules can be used, such as the min normalization, considering the ratio between the value and its minimum figure.

The weights represent the mutual importance of the criteria and are key to the description of the preference model of the decision-maker. In this case, we consider four set of weights for different stakeholder profiles, as reported in Table 2.

**Table 2 Weights attached to the criteria by different stakeholders.**

| Code | Description | Mayor | Environmental group | City user | Resident |
|---|---|---|---|---|---|
| CR1 | Access to for resident people | 0.10 | 0.10 | 0.20 | 0.10 |
| CR2 | Access to wetlands for GI users | 0.10 | 0.25 | 0.20 | 0.10 |
| CR3 | Access to public buildings | 0.10 | 0.10 | 0.30 | 0.10 |
| CR4 | Carbon sequestration in the short run | 0.15 | 0.25 | 0.10 | 0.15 |
| CR5 | Carbon sequestration in the long run | 0.10 | 0.20 | 0.10 | 0.25 |
| CR6 | Cost of construction | 0.25 | 0.05 | 0.05 | 0.20 |
| CR7 | Cost of management | 0.20 | 0.05 | 0.05 | 0.10 |

The values are attributed by experts and reflect the preference model of typical group of individuals. So, the administrator (mayor) is often interested in limiting the cost of construction and management and in solving the concerns connected to carbon sequestration especially in the short run. Environmental groups are usually risk prone to the investment in GI (low weight attributed to the costs) and very interested in enhancing the accessibility to wetlands. The city user is interested in an efficient services delivery: he/she is mostly concerned with the access to public buildings and does not care for the costs, that are being sustained by resident people. Finally, the residents are equally interested to the access to public buildings and amenities, but mostly look at the improvement of local conditions in the long run and in the cost of construction, in terms of monetary resources and problems connected to the workings.

Criteria scores and weights are combined through a very popular aggregation rule in multicriteria evaluation studies, i.e., the weighted summation based on the Multi Attribute Utility Theory (MAUT) and obeying to the following Equation (6):

$$U_i = \sum_{1}^{N} w_{ir} X_{ir} \qquad (6)$$

where $U_i$ is the utility of alternative $i$, $w_r$ is the weight of the $r^{th}$ criterion and $X_{ir}$ is the score of the $i^{th}$ alternative with respect to criterion $r^{th}$. MAUT postulates that selection processes can be addressed by picking the alternative showing the highest utility. Each alternative is assessed through a complex evaluation score considering the level of utility corresponding to various characteristics or attributes (Keeney, 1996). Attributes' utility is measured by criteria scores. Thus, the utility function can be expressed as follows by Equation (7):

$$U_i = w_1 X_{i1} + w_2 X_{i2} + w_3 X_{i3} + w_4 X_{i4} + w_5 X_{i5} - w_6 X_{i6} - w_7 X_{i7} \qquad (7)$$

where in the right-hand term the first five elements stand for the weighted utilities of the benefits associated to the ecosystem services and the last two item for the weighted dis-utilities of the costs.

**Application to a case study of Bordeaux**

Bordeaux is localized in the region New Aquitanian, south-western France and it is the capital of the Gironde department. Twenty-eight municipalities compose a metropolitan area spreading 578.3 $km^2$ (Institut national de la statistique et des études économiques 2022b). Bordeaux hosts 263,247 inhabitants (2020), with a population density equal to 5,286.80 inhabitants/$km^2$. The metropolitan area hosts 814,049 people (2019), with a population density of 1,407.70 inhabitants/$km^2$ (Institut national de la statistique et des études économiques 2022a). Bordeaux is characterized by an Atlantic climate, quite temperate, with dry summers and autumn, and very rainy winter. The medium temperature is 12.7 °C, while medium rainfall are 800 mm (Hubbard et al. 2021). The city is crossed by the Garonne River: on its left bank, the metropolitan city has expanded.

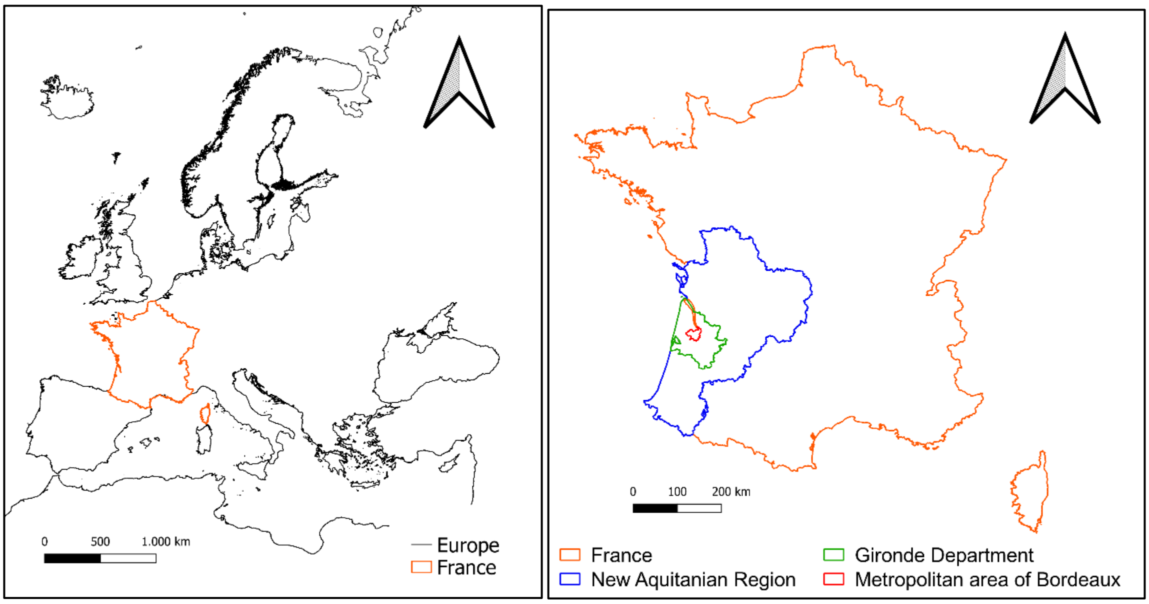


**Figure 2 Localization of France in the context of Europe (left) and metropolitan areas of Bordeaux in its region, department, and France (right).**

In last fifty years, urban sprawl has led to land intake of wide agricultural -mostly viticultural- and forestry areas, triggering a spatial competition between the city and the historical vineyards (CNES 2021). Three relevant viticultural areas survive in the metropolitan area and conserve an agricultural and historic heritage (see Figure 3): Haut-Brion (node 1) localized between Pessac and Talence, Pape-Clément (node 2) localized in Pessac, and vineyards of Château Picque-Caillou (node 3) localized in Mérignac. These wine landscapes reflect the high value of the viticultural activity, with a focus for Haut-Brion, one of the most prestigious wineries in Bordeaux, and represent green nodes in urban area occupied by large residential settlements, sports areas, and university campus (CNES 2021).

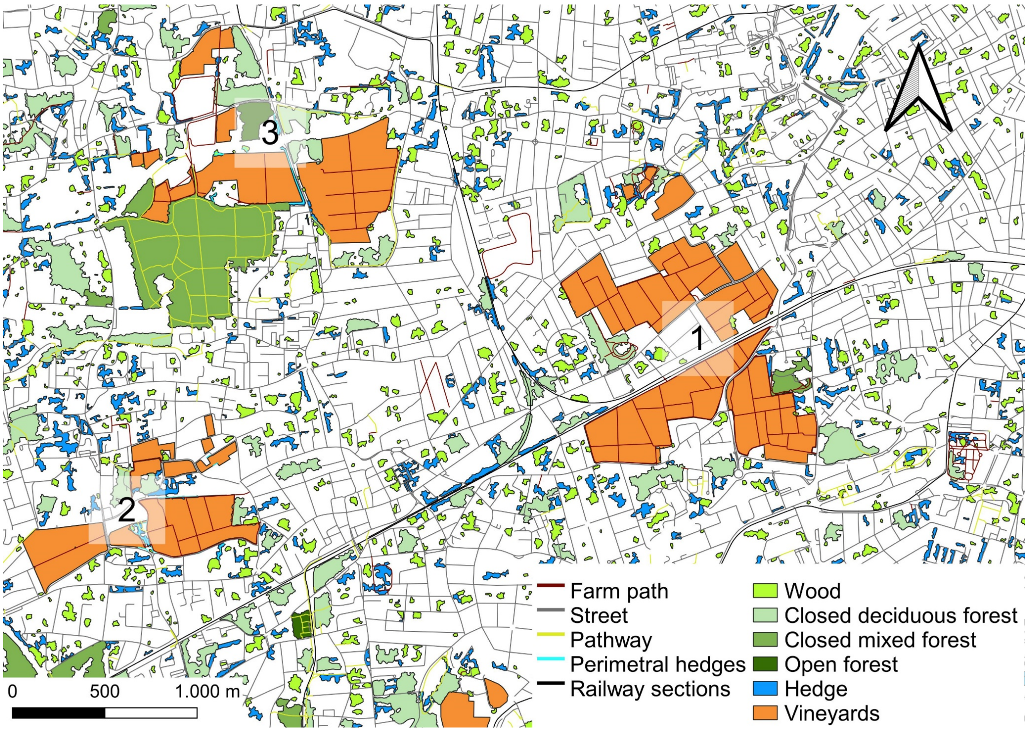


**Figure 3 Land use around three main viticultural areas.**

The main viticultural nodes include paths usually used for farm mobility but also by visitors, cyclists, walkers, and runners. Figure 4 shows parts of the existing paths.

**Figure 4 Examples of small portions of existing paths.**

***Data set adopted***
We applied the method by using data available free of charge from the institutional website of the Institut national de l'information géographique et forestière (IGN)[1] WorldPop[2] and Atelier open data.[3] Data retrieved from IGN include the borders of the metropolitan area of Bordeaux, land use, and transport and mobility infrastructures, and were released in March 2022 (Table 3). We downloaded the files in shapefile format and processed them through QGIS Software.[4] We also used the maps obtained from Google Maps.[5]

**Table 3 Metadata of the geographical information processed in this study (source: geoservices.ign.fr, year 2022).**

| | Description | Type | Format | Geometry | Entities represented |
|---|---|---|---|---|---|
| 1 | Borders | Vector | .shp | Polygon | Metropolitan area |
| 2 | Land use map | Vector | .shp | Polygon | Zones of the master plan |
| 3 | Road sections | Vector | .shp | Line string | Walking paths, cycle paths, gravel roads, single or dual carriageways |
| 4 | Railway sections | Vector | .shp | Line string | Tramway, main railway line, high speed line and service roads |

Table 3 reports on the metadata of the geographic information processed in this exercise. Information on roads is further sub-categorized into aisle, paths, streets, boulevards, stairs, galleries, car parking, climbs, passages, bridges, etc. Data retrieved from WorldPop include the population density (Bondarenko et al., 2020). Population density refers to the estimated total number of people per grid-cell "resolution of 3 arc (approximately 100 m, at the equator)" (Bondarenko et al., 2020). Data retrieved from Atelier open data include the geographical location of public buildings and wetlands (amenities).

**Results**
We structured the application following the MCA application reported before. The first element attains the definition of the alternatives. The GI is meant as a system interconnecting the three nodes illustrated above, through ecological corridors including existing and new supplementary green components, such as hedges and trees. A higher level of connectivity is achievable by designing a semi-natural sustainable signaled route, integrating the existing route structures with natural elements. There are many possible corridors connecting the nodes.
In Figure 5, we identified three alternative paths.

[1] geoservices.ign.fr
[2] https://hub.worldpop.org/geodata/summary?id=49784
[3] https://opendata.bordeaux-metropole.fr/explore/?disjunctive.publisher&disjunctive.frequence&disjunctive.territoire&sort=explore.popularity_score&refine.publisher=Ville+de+Bordeaux&refine.publisher=Bordeaux+M%C3%A9tropole
[4] https://www.qgis.org/it/site/
[5] https://www.google.com/maps/

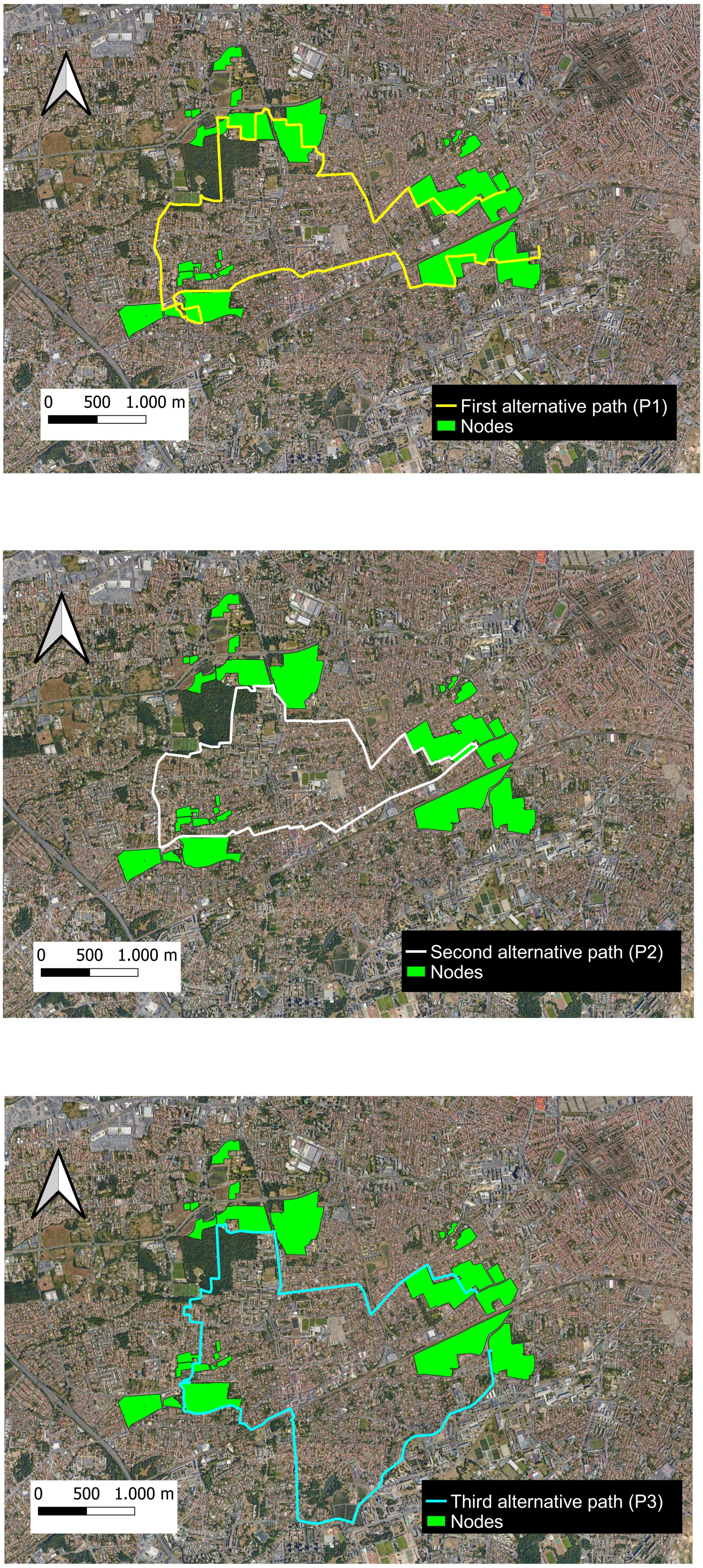


**Figure 5 The alternative paths connecting the nodes of the GI.**

These itineraries are adequately marked with eco-sustainable signs and designed to be accessed by outsiders (e.g., tourists), who will be able to stop by and visit the cellars. The starting and ending points of the route are served by bus stops, to ensure proper accessibility from the city center and vice versa. The route includes an existing cycle path that is projected to be dismantled and refurbished. The model of the new ecological corridors consists of cycle-pedestrian paths separated by row of hedges and a row of trees on the sides of the track. As for the trees, we selected hardwood species voracious of carbon dioxide. According to CICES (cod. 2.3.5.1), carbon (dioxide) sequestration is a regulatory ES, key for reducing greenhouse gas concentration in the atmosphere. We suggest the following species: Common Elm (*Ulmus minor*), Common Ash (*Fraxinum excelsior*), Wild linden (*Tilia cordata*), Hackberry (*Celtis australis*), Curly maple (*Acer platanoides*), Black alder (*Alnus glutinosa*), Silver birch (*Betula pendula*), Turkey oak (*Quercus Cerris*).[6] These species show medium and excellent capacity to absorb gaseous pollutants and dust. These species are not alien (Inventaire National du Patrimoine Naturel)[7] neither invasive (Caillon and Lavoué 2016). The requirements of the flooring include eco-friendliness, recyclability, permeability, and wear-resistance.[8] The path will be realized by using a mixture of soil and recycled stone aggregates able to reduce transport costs and emissions into the atmosphere. The flooring will be rather thick and immediately accessible/walkable. It does not require periodical additions of material, does not produce mud or dust, and prevents potholes.
For each alternative path, we obtained the scores reported in Table 4.

**Table 4 Scores attributed to the alternative paths, according to the criteria.**

| **Alternatives** | **CR1 (1/km$^2$)** | **CR2 (Ha/km$^2$)** | **CR3 (1/km$^2$)** | **CR4 (t/Ha/y $CO_2$)** | **CR5 (t/Ha/y $CO_2$)** | **CR6 (Euro)** | **CR7 (Euro/y)** |
|---|---|---|---|---|---|---|---|
| P1 | 11,74689.61 | 12,879.95 | 23,236.00 | 7.80 | 304.68 | 453,600.00 | 15,120.00 |
| P2 | 11,04933.24 | 6,145.53 | 30,580.00 | 5.73 | 223.88 | 333,312.00 | 11,110.30 |
| P3 | 1,209,144.58 | 7,423.82 | 67,960.00 | 7.31 | 285.72 | 425,376.00 | 14,179.20 |

For the sake of conciseness, we report in Appendix on the rationale and calculations of the scores attributed to each criterion. As the scores in Table 4 are expressed in different units of measurement, we normalize the scores according to the min-max transformation and obtain the score reported in Table 5.

[6] https://www.coldiretti.it/ambiente-e-sviluppo-sostenibile/piante-mangia-smog
[7] https://inpn.mnhn.fr/accueil/recherche-de-donnees/especes/?lg=en
[8] https://terrasolida.it/nature/

**Table 5 Normalized scores of the alternative paths, after the min-max normalization.**

| Alternatives | CR1 | CR2 | CR3 | CR4 | CR5 | CR6 | CR7 |
|---|---|---|---|---|---|---|---|
| P1 | 0.669 | 1.000 | 0.000 | 1.000 | 1.000 | 1.000 | 1.000 |
| P2 | 0.000 | 0.000 | 0.164 | 0.000 | 0.000 | 0.000 | 0.000 |
| P3 | 1.000 | 0.190 | 1.000 | 0.763 | 0.765 | 0.765 | 0.765 |

The combination of the normalized scores with the weights reported in Table 3 leads to four final rankings representing the preferences expressed by the different stakeholders (Table 6).

**Table 6 Final rankings representing the preferences of different stakeholders.**

| Alternatives | Mayor | Environmentalist | City user | Resident |
|---|---|---|---|---|
| **P1** | 0.867 | 0.867 | 0.634 | 0.817 |
| **P2** | 0.016 | 0.016 | 0.049 | 0.016 |
| **P3** | 0.754 | 0.668 | 0.767 | 0.716 |

Path 1 is the most favourite, according to three out of four stakeholders, while Path 3 is the best choice just for the group of city users. The final decision depends on the political attitude of the government and community, provided that Path 1 turns out to be a transversal option encompassing the preferences of large groups of local society.

**Discussion**

In this study, we studied GI planning through ESs assessment in a viticultural area of Bordeaux. We focused on urban vineyards located in the municipality of Pessac and planned a sustainable path able to provide regulating and cultural ESs.

As a first result, we identified three alternative paths with emphasis on different length and direction, unlike Langemeyer et al. (2020) who considered alternatives related to composition and design. Consequently, in terms of ESs the longer the path the more the carbon stored as we might count on more plants along the route than in a shorter path. We selected hardwood species (deciduous trees) voracious of carbon dioxide by avoiding alien (Inventaire National du Patrimoine Naturel) or invasive (Caillon and Lavoué 2016) species. The use of deciduous trees could also be relevant to the GI planning, as these species can contribute to improve citizens' health and their resilience in terms of adaptation to climate change.

However, if we consider the costs, the longest path could not be the best alternative. The preference assigned to a path over another one is strictly related to the weights the stakeholders give to individual criteria such as those listed in Table 2. In this regard, we proposed a method that emphasizes the importance of involving as many actors as possible and proposes a sensitivity analysis, which plays a crucial role in defining the final results.

For each alternative path, we obtained specific (normalized) scores. This step allowed us to compare the preferences expressed by the different stakeholders, with respect to the different ESs - positive (benefits) or negative (costs)- provided by the proposed GI. This framework provides planners and decision makers with important information concerning a variety of stakeholders' preferences. This is relevant to the design of GI rooted in public and private consensus.

As a response to RQ1, which attains the nature and rationale of the methodological approach useful for supporting the design of the most efficient GI, we proposed a multi-criteria-based method for the evaluation of cultural and regulating ESs. The method consisted of defining and comparing three path alternatives, with respect to a set of criteria gauged by different measures, which are related to the two types of ESs considered, and to the preferences of four classes of hypothetical stakeholders. Sensitivity analysis allowed us to compare different rankings associated to the preference systems (i.e., the criteria weights) of each stakeholders' group. We assessed cultural ESs, by using an accessibility model inspired by Geurs and van Wee (2004): the higher the accessibility of the GI, the higher the GI's effectiveness in providing ESs (Ala-Hulkko et al. 2016; Cheng et al. 2019).

RQ2 concerned the ability of the method to consider the balance between the delivery of ecosystem services and the construction and maintenance costs. The proposed method has proven to be useful for comparing positive and negative aspects. Indeed, we considered the benefits related to ESs, but also building and maintenance costs. The identification of the best alternative depends on various explicit and implicit dimensions and factors that need to be considered in the planning and design processes such as, for example, buffer width, carbon dioxide sequestration, construction and maintenance costs, stakeholder opinions, etc. The inclusion of the costs in the criteria is recommended, with respect to approaches focussing exclusively on the benefits; in this paper, we use the net benefit an efficient measure of the viability of the GI alternatives.

RQ3 referred to the exportability of the method to other decisional and planning contexts, in the public domains. In this regard, we can assume that the proposed method based on scientific literature is applicable to other European contexts, where GI planning is directed to the provision of specific ESs (García et al. 2020b; Langemeyer et al. 2020; Li, Uyttenhove, and Van Eetvelde 2020). The methodological approach can be applied for assessing the benefits obtainable from urban agricultural, urban green components, peri-urban green spaces, rural areas isolated and other GIs parts as we considered an urbanized context where extensive viticultural areas represent the urban agriculture nodes. The method has been applied with the purpose of planning a wine's green infrastructure and we feel it can be used in other agricultural contexts as approach to join elements (nodes) belonging to cultural heritage systems. Finally, the proposed ecological path is a component suitable to the implementation of a variety of GI.

Other authors studied the assessment of ESs in a European metropolitan area through multi-criteria analysis method. For example, Langemeyer et al. (2020) and García et al. (2020b) assessed ESs through scores attributed by expert stakeholders to alternatives set with regard to different ESs. Compared to their studies, we measured ESs, by quantifying the criterion associated to each ES. While Li, Uyttenhove, and Van Eetvelde (2020) focused only on one specific ES related to the mitigation of risk associated to flooding in an urban area, we broadened the spectrum of ESs assessed to five ESs belonging to two macro-categories. In addition, we completed the assessment of the alternative paths by including also the measurement of construction and maintenance costs.

This paper contributes to broaden the research strand on the assessment of cultural ESs, often considered unmeasurable, by applying an accessibility-based framework. We believe that, in the planning phase, this model can provide substantial information about the efficiency of a GI. We remark the validity of the multi-criteria method for assessing ESs, as it entails the definition of GI alternatives, with the purpose of providing decision makers with a tool supporting the selection of an effective solution rooted in private and public consensus. The inclusion of costs is crucial to support a careful analysis of *pro* and *cons* of the alternatives.

## Conclusion

This study dealt with the planning of GIs in Bordeaux (France), through ecosystem services (ESs)

assessment. We applied a methodological approach based on multi-criteria analysis to compare and evaluate cultural and regulating ESs typologies expressed by various measures. We based our analysis on three alternative paths of different length and assessed the carbon dioxide sequestration (regulating ES) in the short and long period, and the accessibility (cultural ES) to a set of amenities.
The multi-criteria method applied to the urban viticultural areas of the Metropolitan City of Bordeaux allowed us to design GI alternatives by simulating the involvement of different stakeholders. We feel that this approach can represent a valid GI planning support tool and an effective operational way to include ESs assessment in spatial planning.
However, this study shows limitations that need to be addressed in future research. Firstly, we applied the method on a small surface area of Bordeaux. Enlarging the sample to include other viticultural patches of metropolitan city might provide clearer scenarios. Weakness also concerns the stakeholders' preferences, which in this study is hypothetical although quite reasonable. Application of the method in other geographical contexts, involvement of stakeholders in an actual scenario, and consideration of additional ESs represent insights for future research.

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