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

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Abstract

Excessive anthropogenic activities affect landscape patterns and trigger a decrease in natural capital and the 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). On the other hand, 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, policymakers, and institutional stakeholders with an adequate evaluation tool. The multifaceted nature of ES 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 rigorously and to support participatory and transparent decision-making in the public domain. In this study, we aim to contribute to the integration of GI design into spatial planning, starting with 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.

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Introduction

The world population is constantly increasing (United Nations, 2019), and the use of soil is always increasingly leaning towards urbanization and intensive agriculture. This leads to a decrease in natural capital (Ghofrani *et al*., 2017), including all natural terrestrial and aquatic resources and the atmosphere, able to provide services (Moyzeová, 2018). These excessive anthropic activities have changed the pattern of the landscape (Senes *et al*., 2020), sparking the decline of green areas in urban and peri-urban zones and the loss of services provided by ecosystems, consequently lowering people's well-being (Ghofrani *et al.*, 2017). Restoring degraded green areas and re-naturalizing processes in abandoned natural areas could be achieved by the implementation of green infrastructures (GIs) (European Commission, 2013). GIs are related to nature-based solutions (Andreucci *et al.*, 2019; Senes *et al.*, 2021), with the main feature of multifunctionality, as well as protecting and conserving biodiversity and habitats (European Commission, 2013). GIs can be realized at different scales, based on the ecosystem services (ESs) that can be provided (Langemeyer *et al*., 2020). GIs adopt the same structure as ecological networks but can supply a large range of services, for example, recreational, healthy areas, regulation of microclimate and pollution, *etc*. (Matthews *et al*., 2015; Andreucci *et al*., 2019; Magaudda *et al*., 2020). Hence, GI planning goes through ESs assessment to achieve a successful design and favor the inclusion of GIs and ESs in spatial planning processes, to date not yet effectively diffused (García *et al*., 2020a; Fernández de Manuel *et al*., 2021). Assessment of ESs is a field that needs more extensive investigation and applications to promote appropriate evaluation tools for planners, policymakers, and institutional stakeholders involved in GI planning and design (Langemeyer *et al*., 2016). The multi-faceted nature of ES 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 to contribute to the integration of GI design into spatial planning, starting with 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 an MCA-based method able to combine the assessment of some regulatory and cultural ESs with costs. We apply the method to the selection of the most efficient alternative out of the 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 other decision-making and planning contexts in the public domain.

This paper is organized as follows. In the next section, we review the scientific cornerstones of this study, including GI analysis and planning, ES definition and assessment, and MCA evaluation of ESs. In the section on Materials and Methods, we respectively illustrate the MCA-based method adopted, describe the case study, and the data set adopted. In the following section, we apply the method to the case study of the metropolitan area of Bordeaux and present the results. In the final 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, ES assessment, and MCA. Each concept has been reviewed in the literature, as reported below.

GIs 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 and semi-natural areas planned to provide ESs or benefits for people while safeguarding biodiversity in urban and rural contexts. Even though the European Commission has promoted the adoption of GIs since 2013, the guide to the planning and design of GIs is still under study (Ronchi *et al*., 2020). The inclusion of GIs in spatial planning processes is one of the challenges facing spatial planners (Matthews *et al*., 2015). In different European regions, the integration of GIs in plans/institutional documents is still in its infancy (Di Marino *et al*., 2019; Grădinaru and Hersperger, 2019; De Montis *et al*., 2021; Ledda *et al.*, 2023).

In this respect, local spatial planning is a crucial process to favor GI diffusion on a 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*. (2020) proposed a quantitative evaluation method to identify priority areas by using a quantitative evaluation method based on the use of appropriate indicators.

Langemeyer *et al.* (2020) based their planning method on spatial screening to identify priority areas of the future green roof network in the urban area of Barcelona (Spain). Other authors focused on the 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, such as stakeholders' opinions (Reu Junqueira *et al*., 2022), financial resources (Green City Network, 2018), mapping of green areas (González-García *et al*., 2022), use of indicators (Pakzad and Osmond, 2016; Pakzad *et al*., 2017), *etc*. De Montis et al. (2021) defined a method to draft GI design guidelines as a tool including GIs in spatial planning and decision processes. The tool is based on the following key steps: a study of local policies, context analysis, and stakeholders' involvement. In general, the authors agree that participatory planning of GIs is one of the most effective tools for their adoption and diffusion (Kušar, 2019). Secondly, ecosystems support humans' lives and provide services, *i.e.*, ESs, for their well-being (La Notte *et al.*, 2017). There is no unique definition or meaning of ESs. Fisher *et al.* (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; and iii) ecological components able to provide benefits. According to the common international classification of ecosystem services (CICES) (Haines-Young and Potschin, 2018), ESs are grouped into three main categories associated with 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 the physical and mental states of people).

Fisher *et al.* (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 ES assessment and mapping in spatial planning as a basis for decision-making is still a challenging issue (García *et al.*, 2020a). They claim that ES assessment is a priority for the spatial planning of green areas, including the design of GIs (Ronchi *et al*., 2020). The assessment of ESs includes the observation of ecological aspects as a whole but also of human-centered phenomena related to their final use (La Notte *et al.*, 2017). Different approaches have been used to assess ESs. For example, Zhang and Muñoz Ramírez (2019) used a set of indicators to gauge and map the spatial pattern of ES provision using geographic information system-based advanced spatial analysis of land use data. García *et al.* (2020a) focused on the assessment of ESs classified into the three types proposed by CICES by attributing weight to the corresponding land cover classes. Fernández de Manuel *et al.* (2021) apply an indicator-based method for assessing the spatial efficiency of the urban neighborhoods of Bilbao in terms of the mismatch between ES supply and demand. As a third issue, MCA is a multi-faceted 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 (García *et al*., 2020a; Li *et al*., 2020; Langemeyer *et al*., 2020). Langemeyer *et al*. (2016) review MCA-based approaches to ES assessment and focus on the opportunity to integrate a variety of issues: ecological, social, and economic values, stakeholder preferences, spatial locations, *etc*. Li *et al.* (2020) apply MCA to assess ESs, with respect to the improvement of resilience against urban surface water flood risk at a local scale. They classify areas into three classes with different measures of risk by combining information connected to five indicators that are useful for detecting priority areas in future GIs. Langemeyer *et al*. (2020) applied an 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*. (2020b) used MCA for mapping ES 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. Efficiency can be measured by considering the net benefit associated with each path. So, a major tool is cost-benefit analysis, a traditional tool adopted in environmental and landscape planning for budgeting public infrastructure (Escobedo *et al*., 2011). In our case, the GI is meant to be a common place accessible for free to any citizen, city user, tourist, *etc*. For this kind of public good, 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 modeled as regulatory and cultural ESs. Regulatory ESs refer to the sequestration of carbon dioxide synthesized for vegetal biomass production, which belongs to the class "regulation of chemical composition of atmosphere", code 2.2.6.1 of the CICES V5 guide (Haines-Young and Potschin, 2018). Cultural ESs include walking, discovering cultural heritage through 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) (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, so we focused on these specific ESs. We aim to provide planners and policymakers with a theoretical and practical approach to valorizing 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 limitations 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.

CR1-5 serve as proxies for the benefits a GI can provide and has a positive direction of preference (the higher the score, the higher the utility), while CR6-7 serve as proxies for 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 with ESs falling into different classes, according to CICES. CR1-3 are modeled by invoking the concept of accessibility (Geurs and van Wee, 2004), and CR4-5 represent 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's 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). Eq. 1 can express it:

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

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 β the cost sensitivity parameter" (Geurs and van Wee, 2004).

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

ES, ecosystem service; GI, green infrastructure; CICES, common international classification of ecosystem services.

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

$$A = \sum_{1}^{n} A_i \quad (2)$$

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 Eq. 3:

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

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, and public buildings, located within the four buffers, 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 the power law rule (Eq. 4):

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

where α stands for a variable exponent depending on the resistance of i-th path (we used α=2). The four buffers used to 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 describe population density. Spatial data concerning population density (as well as wetlands and public buildings) have been clipped through QGIS software for each buffer.

CR4-5 concerns carbon dioxide sequestration (CDS) in the short and long run. CDS is assessed by considering the carbon dioxide-vegetable 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. 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 scores 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 minimum 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 sets of weights for different stakeholder profiles, as reported in Table 2. The values are attributed by experts and reflect the preference model of a 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 investment in GI (low weight attributed to the costs) and very interested in enhancing the accessibility of wetlands. The city user is interested in efficient service delivery; he/she is mostly concerned with access to public buildings and does not care for the costs that are being sustained by resident people. Finally, the residents are equally interested in access to public buildings and amenities but mostly look at the improvement of local conditions in the long run and the cost of construction in terms of monetary resources and problems connected to the workings.

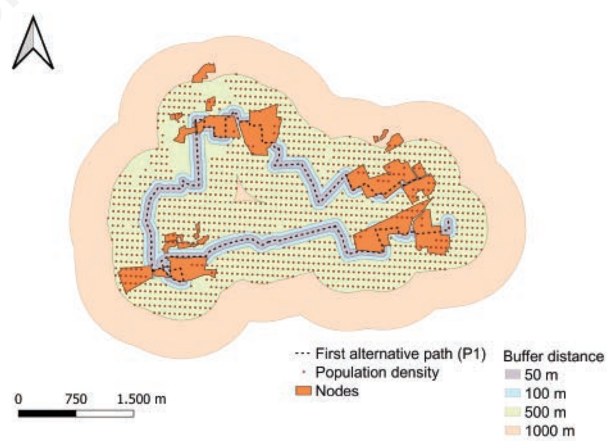

Figure 1. Layout of the four buffers for the first alternative path.

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

Code	Description	Mayor	Environmental group	City user	Resident
CR1	Access to 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

GI, green infrastructure.

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 Eq. 5:

$$U_i = \sum_{1}^{N} w_{ir} X_{ir} \quad (5)$$

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 Eq. 6:

$$U_i = w_1X_{i1} + w_2X_{i2} + w_3X_{i3} + w_4X_{i4} + w_5X_{i5} - w_6X_{i6} - w_7X_{i7} \quad (6)$$

where, in the right-hand term, the first five elements stand for the weighted utilities of the benefits associated with ecosystem services and the last two items for the weighted disutilities of the costs.

Application to a case study of Bordeaux

Bordeaux is localized in the region of New Aquitaine, in southwestern France, and it is the capital of the Gironde department (Figure 2). Twenty-eight municipalities compose a metropolitan area spreading 578.3 km^2 (Institut National de la Statistique et des Études Économiques, 2022a). 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, 2022b). Bordeaux is characterized by an Atlantic climate that is quite temperate, with dry summers and autumns and very rainy winters. The medium temperature is 12.7°C, while the medium rainfall is 800 mm (Hubbard *et al.*, 2021). The city is crossed by the Garonne River; on its left bank, the metropolitan city has expanded.

In the last 50 years, urban sprawl has led to the land intake of wide agricultural (mostly viticultural) and forestry areas, triggering 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 (Figure 3): Haut-Brion (node 1) localized between Pessac and Talence, Pape-Clément (node 2) localized in Pessac, and the vineyards of Château Picque-Caillou (node 3) localized in Mérignac. These wine landscapes reflect the high value of the viticultural activity, with a focus on Haut-Brion, one of the most prestigious wineries in Bordeaux, and represent green nodes in urban areas occupied by large residential settlements, sports areas, and university campuses (CNES, 2021).

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.

Dataset 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) (geoservices.ign.fr), WorldPop (https://hub.worldpop.org/geodata/summary?id=49784) and Atelier open data (https://opendata.bordeaux-metropole.fr/explore/?disjunctive.publisher&disjunctive.frequence&disjunctive.territoire&sort=explore.popularity_score&refine.publisher=V

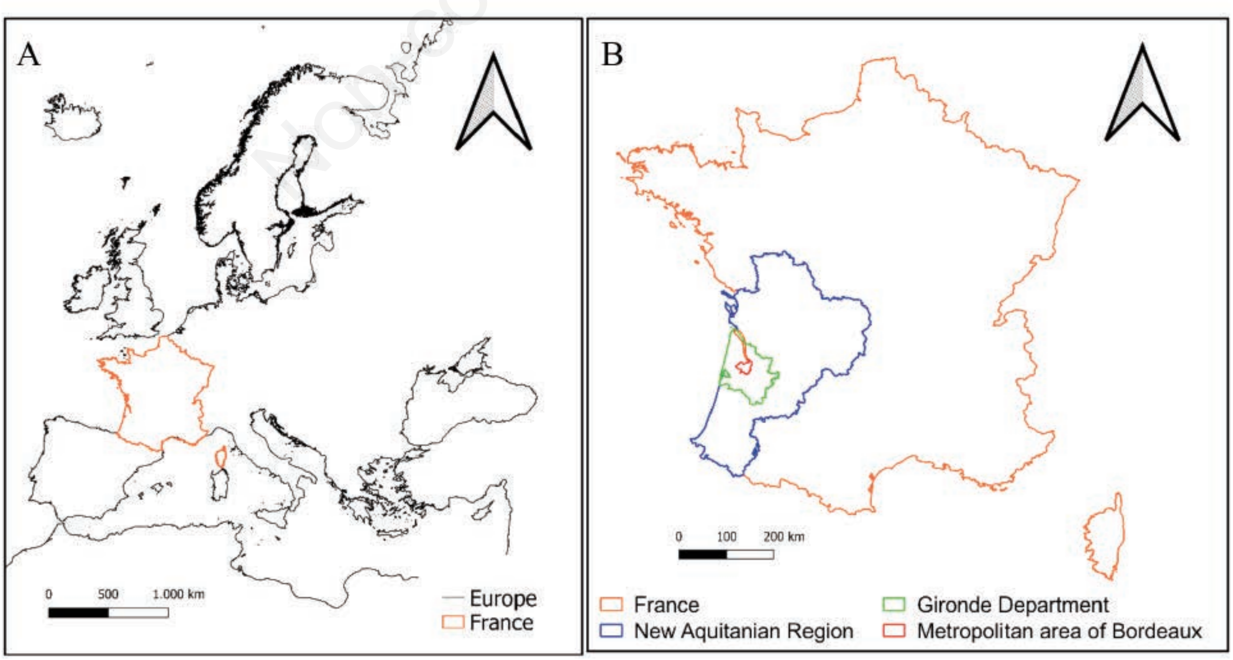

Figure 2. A) Localization of France in the context of Europe; **B**) metropolitan areas of Bordeaux in its region, department, and France.

ille+de+Bordeaux&refine.publisher=Bordeaux+M%C3%A9tropole). 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 (https://www.qgis.org/it/site/). We also used the maps obtained from Google Maps.

Table 3 reports on the metadata of the geographic information processed in this exercise. Information on roads is further sub-categorized into aisles, 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 and integrating the existing route structures with natural elements. There are many possible corridors connecting the nodes. In Figure 5, we identified three alternative paths. 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

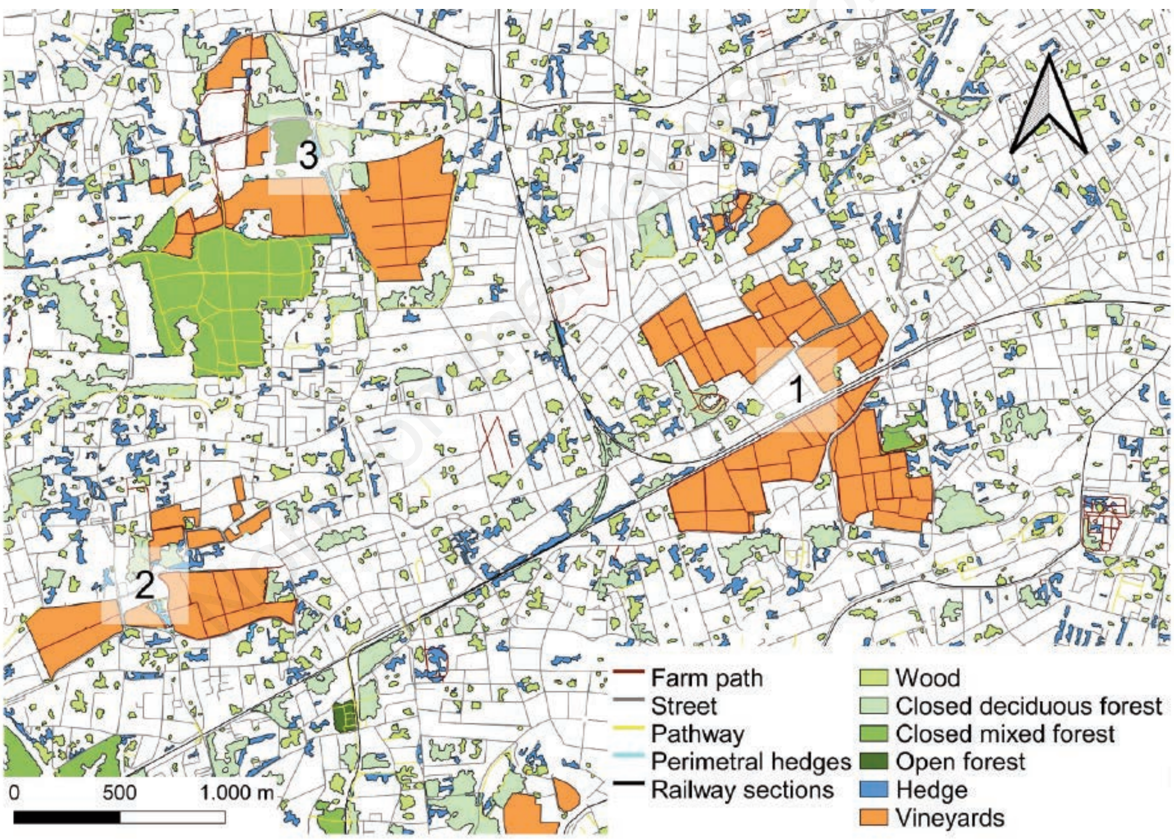

Figure 3. Land use around three main viticultural areas.

Table 3. Metadata of the geographical information processed in this study.

Code	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

dismantled and refurbished. The model of the new ecological corridors consists of cycle-pedestrian paths separated by a row of hedges and a row of trees on the sides of the track. As for the trees, we selected hardwood species that are voracious to carbon dioxide. According to CICES (cod. 2.3.5.1), CDS is a regulatory ES, key to reducing greenhouse gas concentrations 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*) (https://www.coldiretti.it/ ambiente-e-sviluppo-sostenibile/piantemangia-smog). These species show a medium and excellent capacity to absorb gaseous pollutants and dust. These species are neither alien (https://inpn.mnhn.fr/ accueil/recherche-de-donnees/especes/?lg= en) nor invasive (Caillon and Lavoué, 2016). The requirements of the flooring include eco-friendliness, recyclability, permeability, and wear resistance (https://terrasolida.it/nature/). The path will be realized by using a mixture of soil and recycled stone aggregates that can reduce transport costs and emissions into the atmosphere. The flooring will be rather thick and immediately accessible/walkable. It does not require periodic additions of material, does not produce mud or dust, and prevents potholes. For each alternative path, we obtained the scores reported in Table 4. For the sake of conciseness, we report in the *Appendix* 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.

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).

Figure 4. Examples of small portions of existing paths.

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

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

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 favorite, according to three out of four types 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 ES 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 regulatory and cultural ESs.

As a first result, we identified three alternative paths with emphasis on different lengths and directions, unlike Langemeyer *et al.* (2020), who considered alternatives related to composition and design. Consequently, in terms of ESs, the longer the path, the more carbon is stored, as we might count on more plants along the route than on a shorter path. We selected hardwood species (deciduous trees) voracious of carbon dioxide by avoiding alien (https://inpn.mnhn.fr/accueil/recherche-de-donnees/especes/?lg=en) or invasive (Caillon and Lavoué, 2016) species. The use of deciduous trees could also be relevant to GI planning, as these species can contribute to improving 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, which is 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 with 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 not only the benefits related to ESs but also the 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, CDS, construction and maintenance costs, stakeholder opinions, *etc*. The inclusion of the costs in the criteria is recommended with respect to approaches focusing exclusively on the benefits; in this paper, we use the net benefit as an efficient measure of the viability of the GI alternatives.

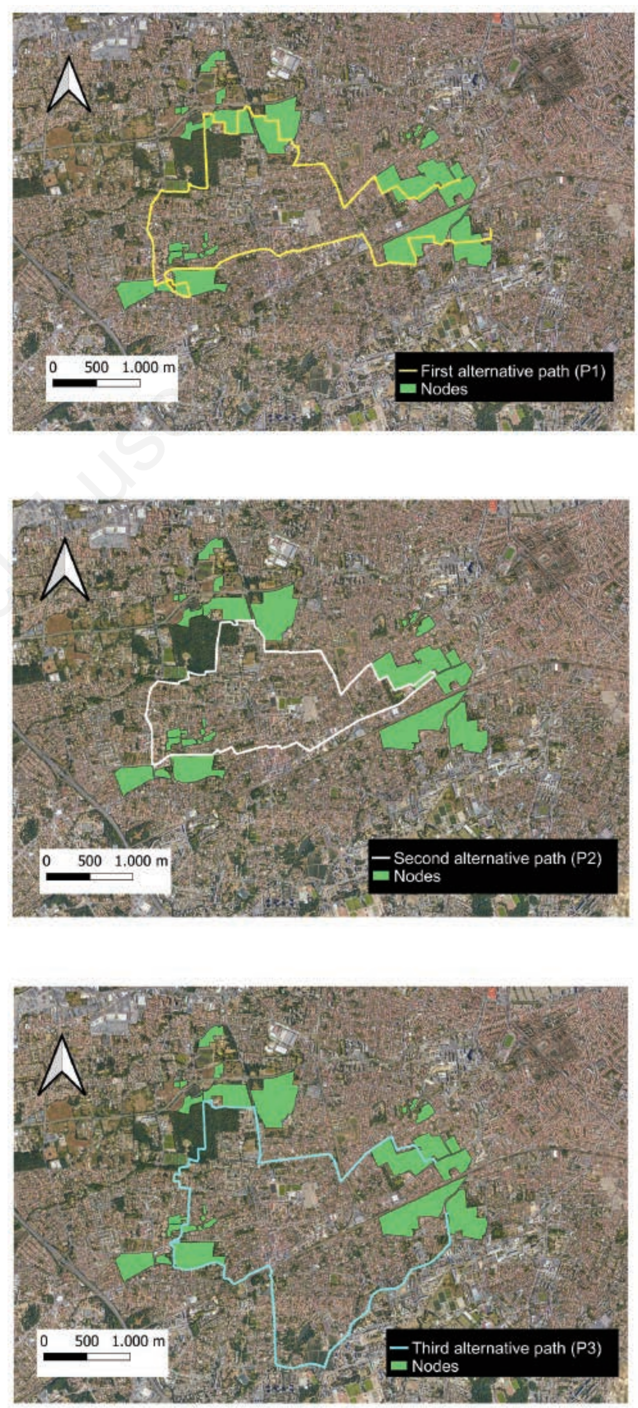

Figure 5. The alternative paths connecting the nodes of the green infrastructure.

RQ3 referred to the exportability of the method to other decisional and planning contexts in the public domain. 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*., 2020a; Langemeyer *et al*., 2020; Li *et al*., 2020). The methodological approach can be applied to assessing the benefits obtainable from urban agriculture, urban green components, peri-urban green spaces, isolated rural areas, and other GIs parts, as we considered an urbanized context where extensive viticultural areas represent the urban agriculture nodes. The method has been applied to plan a wine's green infrastructure, and we feel it can be used in other agricultural contexts as an approach to joining elements (nodes) belonging to cultural heritage systems. Finally, the proposed ecological path is a component suitable for the implementation of a variety of GIs. Other authors studied the assessment of ESs in a European metropolitan area through the multi-criteria analysis method. For example, Langemeyer *et al*. (2020) and García *et al*. (2020a) 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 criteria associated with each ES. While Li *et al.* (2020) focused only on one specific ES related to the mitigation of risk associated with 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 the measurement of construction and maintenance costs.

This paper contributes to broadening 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 on the validity of the multi-criteria method for assessing ESs, as it entails the definition of GI alternatives to provide 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 supporting a careful analysis of the *pros* and *cons* of the alternatives.

Conclusions

This study dealt with the planning of GIs in Bordeaux (France) through the assessment of ESs. We applied a methodological approach based on multi-criteria analysis to compare and evaluate cultural and regulating ES typologies expressed by various measures. We based our analysis on three alternative paths of different lengths and assessed CDS (regulating ES) in the short and long periods 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 ES assessment in spatial planning. However, this study shows limitations that need to be addressed in future research. Firstly, we applied the method to a small surface area of Bordeaux. Enlarging the sample to include other viticultural patches of metropolitan cities might provide clearer scenarios. Weakness also concerns the stakeholders' preferences, which in this study are hypothetical but 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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Online supplementary material:
Rationale and calculations of the scores attributed to each criterion.

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