GIS-based multicriteria land suitability assessment for nature-based solutions for the enhancement of carbon sequestration in Emilia-Romagna, Italy

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ABSTRACT

A GIS-based multicriteria decision analysis (MCDA) is presented to evaluate the suitability of land for the implementation of nature-based solutions (NbS) to enhance carbon sequestration in Emilia-Romagna, Italy. Excessive carbon emissions into the atmosphere have caused rapid and profound climate change that needs to be mitigated. The use of NbS has emerged as an effective strategy to sequester atmospheric carbon and improve environmental resilience. This study focuses on identifying the best NbS to maximise carbon sequestration for three environmental zones: urban, peri-urban and agricultural. The analysis identifies optimal locations for three area-specific NbS: street trees, green spaces and buffer strips. The region was divided into 30 × 30 m grid pixels, with each grid cell assigned a value from 1 (least suitable) to 5 (most suitable). The results show that most of the high-quality pixels are located near the main urban centres and along the coastline. These results provide useful information for policy makers and urban planners who can be guided in the strategic implementation of NbS to achieve maximum environmental benefits. The work also includes an individual sensitivity analysis to validate the robustness of the proposed model and a quantitative estimate of the carbon that can be sequestered by these NbS.

1. Introduction

In recent decades, carbon has become a major concern for humans due to its excessive release into the atmosphere, particularly in the form of carbon dioxide (CO_2) and methane (CH_4). One of the major concerns associated with carbon emissions is their impact on climate change (Yoro and Daramola, 2020). In fact, CO_2 and CH_4 are the two main greenhouse gases (GHGs) that trap heat in the atmosphere, leading to global warming (Stocker et al., 2013). Rising global temperatures have many serious consequences, including the melting of ice caps and glaciers, which leads to sea level rise and more frequent extreme weather events such as hurricanes, droughts and floods (Hansen, Sato et al.,

2015). These changes disrupt ecosystems, threaten biodiversity (Ostberg et al., 2013), and pose direct risks to settlements and infrastructure (Duvillard et al., 2015; Yasuhara et al., 2007) and human health (Ki-Hyun Kim and Jahan, 2014).

It is therefore important to take action to reduce the amount of carbon in the atmosphere. The United Nations has already taken action. They have set a list of seventeen goals to be achieved by 2030, known as the Sustainable Development Goals. Goal number 13 focuses on "climate action" and states the need to "take urgent action to combat climate change and its impacts" (Sachs et al., 2022).

Nature-based solutions (NbS) are among the most promising and sustainable strategies that can contribute to reducing carbon in the

atmosphere (Alves et al., 2019). There are many definitions for this concept (Sowińska-Świerkosz and García, 2022), with one of the most widely used being defined by the Commission & Agency of the European Commission and Agency (2023). According to this definition, NbS are "solutions inspired and supported by nature, which are cost-effective, provide environmental, social and economic benefits at the same time and contribute to building resilience. Such solutions bring more and more diverse nature and natural features and processes into cities, landscapes and seascapes through locally adapted, resource-efficient and systemic interventions".

NbS have the potential to provide net reductions in greenhouse gas emissions, both through carbon sequestration and other mechanisms such as microclimate regulation and behavioural nudging. For example, Pan et al. (2023) assessed 54 European cities and modelled the spatial distribution of different NbS, such as urban forests, green belts and street trees, based on local emission sources and urban contexts. The results suggest that implementation of these NbS could reduce urban carbon emissions by an average of 17.4 %. Wang et al. (2023) discussed how coastal ecosystems such as mangroves, salt marshes and seagrass beds play an important role in carbon sequestration. These ecosystems, known as blue carbon habitats, capture and store significant amounts of CO_2, helping to mitigate climate change. The paper highlights the importance of conserving and restoring coastal areas to increase their carbon sequestration capacity. Xi et al. (2022) studied NbS through green configuration design to optimise urban microclimate and carbon sequestration. Using a community of building complexes as a case study, they evaluated the benefits of different greening patterns (green roofs, street trees and shelterbelts, the combination of planted forests and natural landscape). The results suggest that a combination of street trees and shelterbelts increases environmental benefits and carbon sequestration more than other configurations. Sun et al. (2024) highlighted the role of NbS in enhancing carbon sequestration in the degraded grasslands of the Tibetan Plateau. Their research showed that the implementation of NbS, such as reforestation and sustainable land management practices, can significantly improve carbon storage. Restoring these ecosystems not only increases carbon sequestration capacity, but also provides broader ecological and climate benefits, contributing both to climate change mitigation and local environmental resilience. NbS support many Ecosystem Services (ES), including carbon sequestration (Fang et al., 2024).

Cong et al. (2023) developed a framework for implementing NbS to achieve carbon neutrality in Stockholm County, Sweden, with the aim of identifying local NbS needs, optimal locations and intervention types. Based on interpolation of carbon emission data, assessment of NbS effects and suitability and spatial allocation of NbS interventions, their study showed the benefits that can be achieved by increasing green spaces in urban centres and preserving natural areas in rural and suburban regions, with positive implications for urban planners in maximising NbS benefits for carbon neutrality. The term suitability refers to the final results of the analysis, which may be presented in numerical or cartographic form. A pixel is considered more suitable when its value is closer to 5, the maximum suitability score.

In light of the findings of the same authors, who identified NbS strategies for different spatial settings and their carbon emission mitigation effects on three different sectors (transportation, residential, industry), the process of selecting the most convenient NbS started with an analysis of the implementation priority of the various types of NbS on the aforementioned three sectors. In order to identify the optimal solution for the urban core, emissions data from the Global Infrastructure Emissions Database (GID, www.gidmodel.org.cn/) was employed. The GID is a comprehensive platform designed to quantify greenhouse gas (GHG) and air pollutant emissions from major global anthropogenic sources, with a particular focus on facility-level data (Tong et al., 2019). The disaggregated data includes data for the three sectors considered in this study, namely transportation, residential and industry.

In urban areas of the Emilia-Romagna region, transportation

emissions represent the most significant source of greenhouse gases. Consequently, street trees emerged as the most promising NbS for reducing carbon emissions in urban settings. This is due to their effectiveness in reducing transportation-related emissions, ease of implementation, minimal spatial requirements, which is an essential factor in densely built urban areas, and their well-documented benefits in the scientific literature" (Pan et al., 2023; Pereira et al., 2024).

The highest mean value for the peri-urban areas is observed for the greenbelt. Greenbelts are typically situated in proximity to major metropolitan areas, including London, Frankfurt am Main, and Seoul (Xie et al., 2020). Greenbelts are described as expansive tracts of protected open land situated in close proximity to urban and suburban areas. The primary objective of these greenbelts is to safeguard and conserve land in order to prevent urban sprawl (Han et al., 2022). Additionally, greenbelts may serve as urban ecological corridors, facilitating natural airflow from suburban areas into inner urban zones and thereby mitigating the effects of the urban heat island (Chunyang Zhu and Li, 2017). In addition, greenbelts can enhance air quality and function as carbon sinks. In light of the layout and scale issues associated with an effective design of a proper green belt, with the aim of increasing the implementability of such a design in a broader range of contexts, urban green spaces have been identified as a second target NbS, with similar aims and a structure that is more flexible and scalable. Green areas situated within the boundaries of a city perform a multitude of functions, the majority of which are analogous to those of green belts. Indeed, in addition to carbon sequestration, they can serve to mitigate urban heat (Aram et al., 2019; Oliveira et al., 2011) and enhance biodiversity (Aronson et al., 2017; Threlfall et al., 2017).

Finally, buffer strips were identified as a NbS with considerable potential to facilitate carbon sequestration in agricultural regions (Udawatta and Jose, 2012). They are typically employed as a means of demarcating the boundaries between agricultural fields and water bodies. The principal objective is to mitigate the carbon emissions and prevent or minimise polluted runoff from agricultural activities from entering the water basins (Borin et al., 2005). Furthermore, the potential for carbon sequestration is enhanced when wooded buffers are selected in lieu of grass buffers. The initial implementation may prove less effective in intercepting sediments, yet it offers a multitude of advantages, including carbon sequestration and the regulation of water temperatures (Cole et al., 2020). In general, wooded buffer strips are regarded as effective carbon sinks (Bailey et al., 2009; Salehin et al., 2020).

Based on the state of the art outlined above, the aim of this paper is to define and test a GIS (Geographic Information System)-based multicriteria land suitability assessment model for evaluating the most suitable locations for three types of NbS, namely street trees, green spaces and buffer strips, to be implemented in urban, peri-urban and agricultural areas respectively. The main outcome of the study is to suggest strategic areas where the implementation of NbS would maximise carbon sequestration from the atmosphere in the case study region of Emilia-Romagna. These suggestions may prove useful in supporting the decisions of policy makers and urban planners. In particular, the work presented in this paper addresses the problem of NbS siting using a novel GIS-MCDA (MultiCriteria Decision Analysis) approach. To the authors' knowledge, there have been no previous GIS-MCDA applications to street tree and buffer strip NbS.

2. Materials and methods

2.1. Study area

The GIS-MCDA model is applied to the Emilia-Romagna case study, showed in Fig. 1. The region, situated in the north of Italy, is one of the most industrialised areas in the country and in Europe, with a prosperous economy and a globally renowned agri-food production sector. The region is divided into two parts: the northern section comprises the

Fig. 1. Emilia-Romagna and its location in Italy.

Po Valley plains, while the other half includes the northern section of the Apennine Mountains. Due to its morphology, the region is also susceptible to air pollution, ranking as one of the most contaminated areas in Europe (Carnevale et al., 2015; Ricciardelli et al., 2017).

2.2. Division of study area into environmental categories

The study area was subdivided into three environmental categories (Cong et al., 2023), for which specific models for NbS implementation will be developed. A classification into urban, peri-urban and agricultural areas was employed. The agricultural areas represent a significant proportion of the study area, with the non-urban soil of the Po Valley plain predominantly comprising agricultural fields. Additionally, the Po Valley is recognised as one of the most polluted zones in Europe, making the NbS particularly advantageous for this region. Other rural areas, primarily comprising protected natural areas of the plain and mountainous regions situated distant from carbon emission sources, were not included in this assessment.

The selection of parameters for the subdivision of the study area into three categories is a complex process, with numerous studies presenting a variety of potential approaches. However, no single approach has been universally designated as the definitive one. As Short Gianotti et al. (2016) observe, there is a paucity of consistency in the methods employed to define urban, suburban, and rural areas. However, it is essential to consider the geographical, social, and economic characteristics in each case (Sahana et al., 2023). Defining the boundaries of the peri-urban areas is key in this study; once this has been completed, the urban and agricultural areas can then be defined with greater ease. However, there is no consensus in the literature regarding the criteria for an area to be designated as 'peri-urban'. Consequently, these 'transitional spaces' remain poorly defined, both in geographic and conceptual terms. In terms of geography, these areas are characterised by a combination of land use and livelihoods, exhibiting attributes of both urban and rural settings. They are situated at a transitional point between the urban core and the rural landscape (Gonçalves et al., 2017). In general, peri-urban areas have a higher population density than agricultural areas and contribute a greater proportion of GDP (van Eupen et al., 2012). A review of the literature reveals that the most common criteria

used to delineate the boundaries of peri-urban areas are population density, building density, and road network density (Gottero et al., 2023; Fang and Wang, 2018; Sutton et al., 2010; Rahimi, 2016). However, there is no consensus on the numerical thresholds that should be used to define the boundaries of peri-urban areas. These thresholds must be tailored to the specific criteria and considerations of the respective case studies, which differs from the context of this work.

The analysis in this study was based on data available for the census divisions provided by ISTAT (Italian National Institute of Statistics, www.istat.it), which comprises a dense network of polygons with high granularity, rendering it particularly useful for the spatialisation of various data. For the purposes of this study, the census divisions have been assumed to represent the spatial units for the classification of the areas in question as urban, peri-urban or agricultural. The census divisions were intersected with the 2020 land-use maps of the Emilia-Romagna region (source: Geoportale Regione Emilia-Romagna 2024 https://geoportale.regione.emilia-romagna.it/) using overlay mapping.

The management and processing of spatial data were conducted using ArcGIS Pro 3.2.2, together with its associated plug-ins and tools.

The initial step involved the identification of urban areas. This was achieved by selecting all census divisions with at least 90 % of their area occupied by artificialised territories, as defined by the Corine Land Cover land-use categories (Copernicus, https://land.copernicus.eu/en/products/corine-land-cover). The exclusion criteria included villas, agricultural and livestock settlements, isolated residential structures and the road network. As mentioned earlier, since there is no universally accepted or official method for classifying areas into the three different environmental categories, for peri-urban areas, this study defines them as the census divisions that directly border the previously classified urban census divisions, following the methodology outlined above. The remaining census divisions with prevailing agricultural use were classified as agricultural areas. Areas classified as forestry and natural areas, wetlands and water bodies were excluded from the domain of the study. The result is shown in Fig. 2.

2.3. The GIS-MCDA process

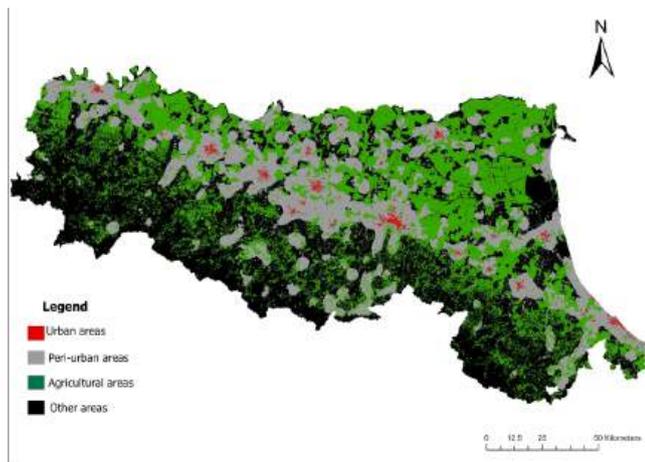The methodology proposed in this work is a GIS-MCDA process,

Fig. 2. Classification of the study areas into urban, peri-urban and agricultural areas.

which combines GIS analysis with a multicriteria decision analysis. MCDA is a decision-making analysis that is employed to address problems that are characterised by a multitude of choices among alternatives, thereby assisting decision-makers in selecting the optimal solution. The integration of GIS and MCDA, known as GIS-MCDA, is a widely used and effective approach for the resolution of a variety of spatial problems. The methodology combines geographic data with decision-makers' preferences to create a decision map, which can subsequently be utilised by planners (Malczewski and Rinner, 2015). This work will primarily focus on the quantitative use of GIS combined with the MCDA technique, which allows the usage of tools that enable the simultaneous analysis of multiple criteria (Malczewski, 2006). In particular, GIS technologies enable the identification and assessment of factors, collating this data in a spatial database, which is highly effective for addressing a range of spatial issues, including spatial optimisation, land suitability, and site selection (Church, 2002; Tassinari and Torreggiani, 2006). GIS has long been a crucial tool for addressing environmental challenges. It has been widely applied to study changes in land cover and land use (Bičík et al., 2012; Hussain et al., 2019; Pelorosso et al., 2009; Shalaby and Tateishi, 2007), which are strongly linked to climate change (Barati et al., 2023). Furthermore, GIS is frequently used to identify and manage areas with ecological potential (Castro and Rifai, 2021; Lami et al., 2024; Xie et al., 2015). Beyond quantitative analysis, GIS is also employed in qualitative assessments, such as evaluating landscape quality (Dong et al., 2022; Stemmer et al., 2021; Vizzari, 2011). The key steps typically involved in a GIS-MCDA process integrate various environmental indicators grouped into various sub-categories. Environmental variables are classified into suitability classes based on statistical distributions and experts' opinions and then combined to generate suitability maps. GIS-MCDA results analysis allows to reveal that most decisive factors, even playing a limiting role (Ozkiper et al., 2024)

The steps of the MCDA process implemented in this research are illustrated in Fig. 3, and their explanations are summarized below.

- Goal: This study aims to develop and validate a GIS-based MCDA land suitability assessment model for identifying the most suitable locations for three types of NbS across three distinct environmental settings.
- Criteria identification: Each NbS type requires specific evaluation criteria, which are identified in subsequent sections.
- Initial settings: The data structure and software environment were defined to ensure systematic analysis.
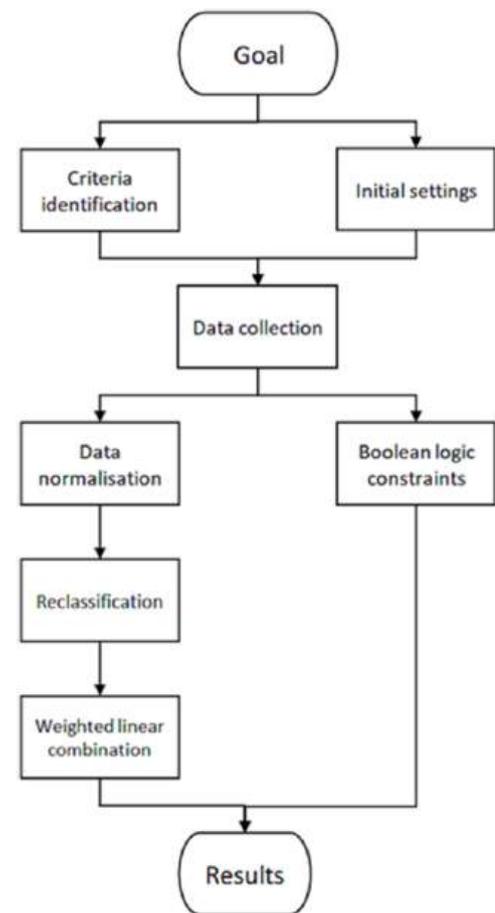- Data collection: Relevant datasets were acquired, organised and pre-processed to meet analytical requirements.

Fig. 3. Flowchart of the GIS-MCDA process.

- Data normalisation: All datasets were converted into raster format and standardised to a uniform pixel resolution of 30 × 30 m².
- Reclassification: Data layers were reclassified into suitability classes ranging from 1 (least suitable) to 5 (most suitable), with 0 indicating areas unsuitable for NbS implementation. Reclassification is a necessary step in the process of standardising diverse data types, thereby ensuring their comparability and usability.
- Weighted Linear Combination (WLC): Criteria were assigned weights based on their relative importance in the analysis and the ranking method describe further in the text. The process of weighting entails the assignment of varying levels of importance to the criteria included in the model. WLC method is executed in the GIS model through map algebra operations (Dana Tomlin, 1990). This approach entails the assignment of a weight to each criterion in accordance with its relative importance.
- Boolean logic constraints: Areas unsuitable for NbS implementation were excluded from consideration.
- Results: The final phase involved aggregating and interpreting the suitability assessment results. Aggregation combines the aforementioned criteria to produce a final suitability map, which can then be delivered to stakeholders and decision makers.

Although Weighted Linear Combination (WLC) methods can be implemented using both vector and raster formats, the latter is often considered more effective and is better supported by GIS software. In this study, the initial data, which were originally in vector format (e.g., points, lines, or polygons), were converted to raster format prior to the analysis. Furthermore, all raster layers were required to have the same extent and pixels that were perfectly aligned. The spatial resolution of this study is 30 × 30 m², corresponding to a pixel size of 30 × 30 m².

The coordinate system employed is that of the official Emilia-Romagna system, designated RDN2008 UTM Zone 32.

2.4. Criteria identifications

A further crucial stage in the GIS-MCDA process is the identification of the criteria to be considered and their relative importance within the model. In the context of this study, several criteria were selected, with each criterion specific to the respective NbS under consideration. The pertinent criteria were identified through an exhaustive examination of the scientific literature pertaining to each of the three NbS. The following paragraphs will illustrate the steps involved in each of these processes.

1) Street trees

The tree species selected for use in street trees, specifically in the climate of Northern Italy, is the evergreen oak (Quercus ilex). This tree does not exhibit excessive growth problems and typically reaches a maximum height of 15–20 m, making it suitable for a dense urban environment. It is particularly well-suited to regions with hot summers and mild winters, which are typical of Emilia-Romagna, especially the coastal and internal plateau regions. It is a species that flourishes in full sun or in the partial shade that is characteristic of its natural habitat (San-Miguel-Ayanz et al., 2016). The optimal temperature is approximately 22.5°C. The species demonstrates considerable ecological plasticity, enabling it to flourish in a wide range of bioclimatic conditions, with the exception of those characterised by extreme aridity, where annual precipitation is below 450 mm. Furthermore, it has a significant capacity for carbon sequestration, with the potential to absorb a considerable amount of carbon particularly in mature trees (Fiorani and Punzo, 2021).

The criteria identified for the GIS-MCDA in relation to street trees are as follows:

1. Carbon emissions
2. Temperature
3. Solar radiation
4. Precipitation
5. Wind strength

These criteria were selected as key parameters for the GIS-MCDA analysis because they support tree health, promote long-term growth, and directly impact carbon sequestration. Since an ability of a tree to capture carbon is closely tied to its overall health, ensuring optimal growing conditions maximises the ecological benefits of the evergreen oak. This enhances its effectiveness as a NbS for carbon sequestration in urban areas.

The carbon emission data were calculated using a model described in paragraphs 2.6 and 2.7. All other data were sourced from the Emilia-Romagna Regional Cartographic Archive (Archivio Cartografico).

The temperature, solar radiation, precipitation and wind strength criteria were calculated using the IDW interpolation method.

Only pixels where streets are present were considered, and only in urban areas, as this is the NbS selected for the urban core. Furthermore, only three categories of streets were considered: primary, secondary, and tertiary, as defined in OpenStreetMap (OSM), to exclude narrow streets in urban centres, where tree planting may encounter challenges.

The relative importance of each criterion within each environmental category was determined through the ranking method, as proposed by Malczewski and Rinner (2015), according to the following formula:

$$w_k = \frac{n - p_k + 1}{\sum\limits_{k=1}^{n} n - p_k + 1}$$

where w_k is the k-th criterion weight, n is the number of criteria under consideration ($k = 1, 2, …, n$), and p_k is the rank position of the criterion.

The method has been employed in numerous GIS-MCDA applications, including those of Jankowski et al. (2008), Proulx et al. (2007) and Zucca et al. (2008).

The importance of the criteria was determined with the understanding that the objective of the NbS is to maximise the potential for carbon sequestration. Accordingly, the criterion pertaining to carbon emissions was accorded the highest level of importance. The wind strength criterion was considered to be of minimal importance, given that strong gusts have the potential to damage trees. However, this does not preclude the NbS from thriving. The variables of temperature, solar radiation and precipitation are of paramount importance for the tree. In the absence of robust scientific evidence, it was not feasible to establish a relative importance ranking. The weights have been refined based on the findings of the sensitivity analysis (described in section 3.6).

1. Carbon emissions (the higher the better; weight: 0.333)
2. Temperature (the closer to 22.5 C the better; weight: 0.267)
3. Solar radiation (the higher the better; weight: 0.2)
4. Precipitation (the closer to 450 mm the better; weight: 0.131)
5. Wind strength (the lower the better; weight: 0.067)

2) Green spaces

Green spaces are defined as 'open areas where the land is partly or completely covered with grass, trees, water sources, shrubs, or other types of vegetation' (Vidal et al., 2020). In this study, the term "green spaces" specifically refers to those classified under level 1 by Madureira and Andresen (2014), which include public gardens and parks. In order to enhance biodiversity, the preference was to create a variety of species in parks (Ren et al., 2017). GIS-MCDAs have already been successfully deployed in green space applications. There are numerous examples in the literature, including Gelan (2021), where the author applied a GIS-based analysis to emerging towns in Ethiopia. Abebe and Megento (2017) described the use of a GIS-MCDA to identify the optimal location for green spaces in Addis Ababa, Ethiopia. Ustaoglu., (2022)) conducted a similar analysis for the Pendik district of Istanbul, Turkey; Osseni et al. (2023) investigated the optimal locations for urban green spaces in the Abomey-Calavi District, Southern Benin; Milošević et al. (2023) did the same in Zadar, Croatia. The latter paper focused on an area similar to Emilia-Romagna in terms of environment and climate (Zadar is located on the other side of the Adriatic Sea at the same latitude), but different in terms of domain extent, as it was a city-scale study rather than a regional one.

Based on an analysis of the scientific literature and the specific goals of this study, carbon emissions were identified as the most significant criterion, with all other criteria then reclassified in proportion according to the paper just cited by Milošević et al. (2023). As in the previous case, the weights have been fine-tuned based on the results of the sensitivity analysis (section 3.6).

1. Slope (the lower the better, weight: 0.25)
2. NDVI (the higher the better; weight: 0.214)
3. Accessibility (the farther from parks the better; weight:0.179)
4. Carbon emissions (the higher the better; weight: 0.143)
5. Road distance (the closer the better; weight: 0.107)
6. Land cover (reclassification based on Li et al.; 2018; weight: 0.071)
7. Residential object density (the higher the better; weight: 0.036)

Data pertaining to land cover, residential object density, accessibility and road distance was sourced from the Emilia-Romagna regional cartographic archive. The carbon emission data were calculated using a model described in Sections 2.6 and 2.7. The slope data were sourced from the NASA Earthdata search portal (www.search.earthdata.nasa.gov). In conclusion, the NDVI data were sourced from the Landsat 8 – 9 OLI/TIRS using images

captured at the beginning of September 2023 via the Earth Explorer platform (usgs.gov.earthexplorer).

The residential object density criterion was calculated by applying the natural breaks method to the percentage of built areas in each census section. In order to calculate accessibility and road distance, the distance from parks and roads, respectively, was considered. The slope criterion was calculated using the slope tool in ArcGIS, which was applied to the digital elevation model (DEM) data. The NDVI criterion was calculated using the raster calculator with satellite data.

3) Buffer strips

In the case of the buffer strips, the weights were determined using the ranking method. In this context, carbon emissions were identified as the most significant criterion, as in the two previous NbS, as the primary objective of this study is to maximise carbon sequestration. Placing NbS closer to highly polluted areas is therefore prioritised to enhance their effectiveness in mitigating emissions.

The wind strength is the least important factor for the reasons previously stated. The function of buffer strips as a barrier to prevent pollution entering the hydrological network was found to be of greater relevance than flood risk reduction in terms of evidence-based benefits, based on an analysis of the scientific literature (Dunn et al., 2022; Mullan et al., 2016). Accordingly, a greater weight was attributed to the barrier criterion. This weighting approach ensures that the criteria are aligned with the primary objectives of buffer strip NbS within the specific study context. The silver poplar (Populus alba) was identified as the most appropriate tree species for the purposes of this study. It has a robust carbon sequestration rate, is indigenous to the Emilia-Romagna region, and has been employed in other investigations concerning buffer strips (Fortier et al., 2010). The following list details the relative importance of the identified criteria:

1. Carbon emissions (the higher the better; weight: 0.25)
2. Proximity to water bodies (the closer the better, weight: 0.214)
3. Flood sensitivity areas (located in more sensitive area; weight: 0.179)
4. Solar radiation (the higher the better; weight: 0.107)
5. Precipitation (the closer to 550 mm/year the better; weight: 0.107)
6. Temperature (the closer to 18.5 C the better; weight: 0.107)
7. Wind strength (the lower the better; weight: 0.036)

The carbon emission data were calculated as described in Sections 2.6 and 2.7. Data for all other criteria were sourced from the Emilia-Romagna Regional Cartographic Archive.

In order to calculate the proximity to water bodies criterion, the distance from the aforementioned water bodies was measured. The cartographic archive already contained the data pertaining to the flood sensitivity areas. The remaining criteria were calculated in accordance with the aforementioned methodology.

2.5. Carbon emission model

In this study, four primary sources of carbon emissions were considered: transportation, industrial, residential and agricultural emissions. This selection was based on existing literature, which identifies these sectors as the most significant contributors to carbon emissions (Huang et al., 2018; Shukla et al., 2022). In particular, in the Emilia-Romagna region, emissions predominantly originate from these sectors, with key sources including domestic heating (residential), street transportation (transportation) and energy production (industrial) (Agostini et al., 2024). As previously stated, one of the most crucial datasets is that pertaining to carbon emissions. Due to the inadequate spatial resolution of the GID model (Tong et al., 2019) (10×10 km²), carbon emissions were calculated separately for four principal sectors: transportation, industrial, and residential emissions (Cong et al., 2023),

as well as agriculture. These were subsequently aggregated and compared with the GID model to validate the results.

1) Transportation emissions

The calculation of transportation emissions has previously been conducted using road and railway density as a proxy (Shu et al., 2010). The data were extrapolated from the official land cover of Emilia-Romagna, and the density was calculated using the specific function of line density on ArcGIS Pro.

2) Industrial emissions

In order to calculate the intensity of carbon emissions from industrial sources, the distance from industrial sites was used as a proxy. These sites included commercial ports, freight sorting facilities, technological plants, commercial and service settlements, and production settlements. The data source for this information was the official land use of Emilia-Romagna of 2020 (Beketie et al., 2022).

3) Residential emissions

The residential carbon emission was calculated on the basis of population density and building density (Cong et al., 2023). The initial calculation was performed using the official Italian census data, which was subdivided into census sections for the region. The building density was calculated using the census section and the official data pertaining to the building maps of Emilia-Romagna.

4) Agricultural emissions

The agricultural emissions are contingent upon the density of livestock farms, particularly cattle and pigs (Ghassemi Nejad et al., 2024). Cattle and pigs are the most prevalent livestock species in Emilia-Romagna. The data pertaining to pigs and cattle were sourced from www.livestockdata.org. Furthermore, the use of fertilisers on arable land (Pant, 2009) has been identified as a factor influencing emissions. Consequently, data pertaining to the official land use of Emilia-Romagna, specifically the category of arable land, has been employed in this analysis. The proportion of fertilised land within each census section was calculated in relation to the total area of arable land. In addition, agricultural emissions are also caused by agricultural operations such as tillage, sowing, harvesting and transportation, water pumping, grain drying, manufacturing, packaging and storing fertilisers and pesticides (Lal, 2004). The aforementioned data were extrapolated from the official land use of Emilia-Romagna using the category "Rural settlement," and the agricultural emissions from the rural settlement were calculated on the premise that these emissions decrease with distance from the settlements. Based on these findings, carbon emissions from the agricultural sector have been estimated according to the following four criteria: areas of rural settlement, hectares of arable land, number of cattle and number of pigs.

2.6. Aggregation of emission factors

These emissions were aggregated to create a final and unique model of carbon emission, based on emission intensity.

Emission data have been weighted, based on the importance of the various sectors as derived from the analysis of the scientific literature (Ritchie, 2020). The weights given to the sectors are as follows:

- Industry 0.294
- Transport 0.123
- Residential 0.175
- Agriculture 0.201

In the context of the industry sector, the categories "Energy use in industry" and "Direct industrial processes" were consolidated into a single unit. In the case of the transportation sector, the values pertaining to "road transport" and "rail" were aggregated. Other sectors, including pipeline, shipping, and aviation, were excluded due to limitations in the availability of data. In the case of the residential sector, the category

"Energy use in buildings" was deemed to be a pertinent consideration. In the case of the agricultural sector, both "Energy use in agriculture and fishing" and "Agriculture, Forestry and Land Use" were taken into consideration. It should be noted that certain sectors were not included in the analysis as they are not encompassed by the four emissions that were taken into account. These are the sectors of waste, the aforementioned transport section, the sector of unlocated fuel combustion, and the sector of fugitive emissions from energy production. These sectors collectively account for 20.7 % of global greenhouse gas (GHG) emissions. The weights were adjusted in proportion to account for this value.

In instances where emission factors were associated with multiple GIS layers, they were distributed proportionately across all relevant layers. In particular, the two layers related to carbon emissions from the residential sector, namely building density and population density, were assigned half of the residential sector criterion, which is 11.0 %. The number of cattle and pigs were assigned a value of 3.66 %, while the remaining was distributed between arable land and rural settlements, with each receiving a value of 9.01 %. Table 1 presents the finalised weights for each emission sector, together with an indication of the contributing factors.

Following the weighting phase, the layer resulting from the proposed model (Fig. 4) was reclassified into five classes (class 1 representing the lowest and class 5 representing the highest). This was achieved through the utilisation of the Jenks natural breaks algorithm, a data classification method that is employed to optimise the grouping of data values into distinct categories. The objective is to minimise the variance within each class and maximise the variance between classes, thereby identifying the natural groupings in the data (Jenks, 1967). This technique is frequently employed in studies utilising geographic information systems (GIS) (Çetinkaya et al., 2016; Mentzafou et al., 2021; Milošević et al., 2023; Mohamed Mouhoumed et al., 2023). The method operates by calculating class breaks that optimise the grouping of similar values and maximise the differences between classes. The method involves an iterative process of adjusting the break points in order to reduce the sum of squared deviations from the class means within each group. This results in a more meaningful categorisation of the data (Jenks, 1967). The model was subsequently downscaled to a resolution of $10 \times 10 \text{ km}^2$ in order to facilitate comparison with the GID model, which was also reclassified into five classes using the Jenks method (Fig. 5). A systematic comparison of the two models was conducted by subtracting the two layers using the Raster Calculator tool (GID model Carbon emission model). Table 2 presents a summary of the results of the raster calculation.

The results vary from $+ 4$, which represents the maximum increase in emission compared to the proposed emission model, to -4, which represents the opposite condition. A value of 0 indicates perfect alignment between the two models. This value is the most frequently observed outcome, followed by -1, -2, and $+ 1$.

A visual representation of the comparison is also provided in Fig. 6, where the predominant colour is green, indicating a high degree of similarity between the two models. The central values of $+ 1$, 0 and -1 collectively represent 80.6 % of the total number of pixels. It can therefore be concluded that the proposed carbon emission model is validated, as it provides results that are consistent with those of the GID model.

Table 1
Types of pollutant emissions and their importance.

Type of emission	Weights
Industry	0.370744
Transport	0.155107
Population density	0.11034
Building density	0.11034
Areas of rural settlements	0.090164
Arable land	0.090164
Number of cattle	0.03657
Number of pigs	0.03657

model.

2.7. Carbon sequestration potential calculation

The final stage of the study entailed the calculation of the potential carbon sequestration capacity of the NbS under investigation. The mean quantity of carbon that can be sequestered per square metre has been determined through the Net Ecosystem Productivity (NEP) of the tree species and multiplied by the number of pixels classified as classes 4 or 5 after the GIS-MCDA, namely, the most suitable sites.

1) Street trees

Firstly, the actual situation regarding street trees was compared with the hypothesis of planting trees along specific street typologies (only those classified as primary, secondary, and tertiary in OSM, as previously mentioned). The existing data pertaining to street trees were downloaded from OpenStreetMap (OSM) via ⟨http://www.overpass-turbo.eu⟩. Due to the unavailability of data at the regional level, it was not possible to download data for the entire region and the city of Bologna was selected for detailed analysis. Pixels were excluded if street trees were already present. The Quercus ilex has been found to sequester, on average, 1288 ± 83 gC·m^{-2}·yr^{-1} (Baldocchi et al., 2010). The project employs a spatial resolution of 30 m x 30 m^2, which, when considered alongside the findings of Park et al. (2019), who determined that an optimal spacing between street trees is 11 m, allows for the estimation that there may be space for approximately five trees per pixel on average, inclusive of both roadsides. A tree of medium size and semi-mature age would typically occupy a diameter of approximately 6 m of tree canopy, resulting in an average coverage of approximately 28 square metres per tree. Therefore, on average, a pixel would be occupied by street trees to the extent of 140 m^2.

2) Green spaces

A generic green space of $20 \times 20 \text{ m}^2$ absorbs on average 223.4 gC·m-2·yr-1 (Zhang et al., 2024).

3) Buffer strips

As for the previous cases, it is possible to calculate the average C sequestrated yearly by a *Populus alba* with the NEP, which is between 96 to 199 gC·m^{-2}·yr^{-1} (Verlinden et al., 2013). The average value between these two numbers has been used, 147.5 gC·m^{-2}·yr^{-1}.

3. Results

3.1. Presentation of the suitability analysis

A thematic map is created for each NbS, with each criterion assigned a value raging from 1 (least suitable) to 5 (most suitable). These maps are then merged with the WLC process according to the assigned weights.

1) Street trees

As mentioned already, only pixels on three typologies of roads within urban areas were considered. The case of the municipality of Bologna, the capital and largest city of Emilia-Romagna, is presented in Fig. 7, since the result would not be visible at the scale of the Emilia-Romagna region.

The graphical results represent a good overall image of the situation of this NbS in the territory of Emilia-Romagna. The majority of pixels (87 %) fall into class 3, with only a few assigned to other classes.

Most pixels are classified as class 3, though a few exceptions are present. The majority of the classified 3 and 4-class pixels can be found in the main roads surrounding the centres of cities and towns.
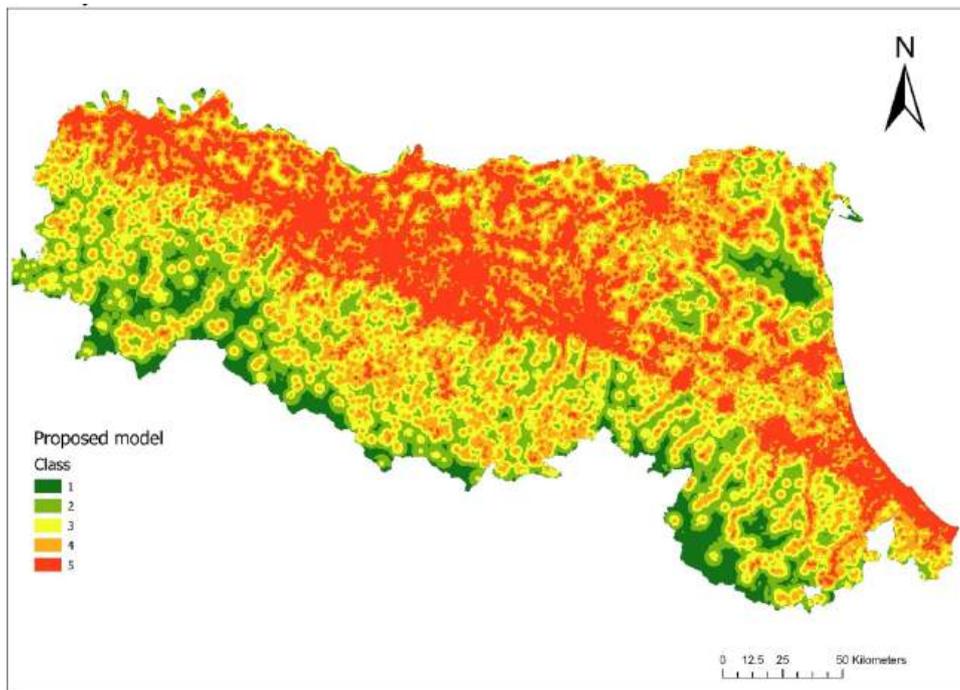
1) Green spaces

Fig. 4. Result of the proposed carbon emission model. Green classes depicted in green (1 and 2) represent where the carbon emissions are lower. Red classes depicted in red (4 and 5) represent where the carbon emissions are higher.

Fig. 5. GID model after the reclassification. Green classes depicted in green (1 and 2) represent where the carbon emissions are lower. Red classes depicted in red (4 and 5) represent where the carbon emissions are higher.
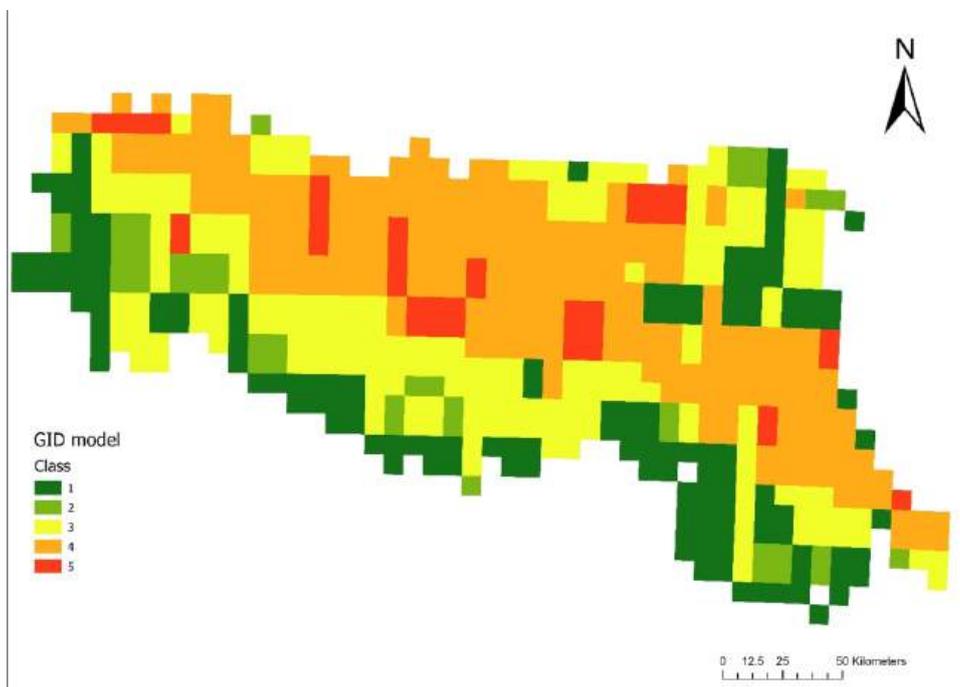
In the case of green spaces, only those located in peri-urban areas are considered. The situation is markedly distinct from that previously described, with considerable variability in suitability across the study area domain, with the majority of pixels classified as 3 or 4 (see Fig. 8).

The numerical results are presented in the Table 4:

In general, green spaces are more readily accessible in the vicinities of major urban centres and towns throughout the region, where most of the peri-urban environment is situated. The higher suitability classes are more readily identified in the relatively flat northern regions and in areas near the coastline

2) Buffer strips

In this case, only the agricultural areas are considered. Fig. 9 illustrates the high variability in suitability at the regional scale, with the majority of pixels classified as 3 or 4 (see Table 5 for the full numerical

Table 2
Result of the comparison between the GID model and the proposed model.

Class	Count	Percentage
−4	2	0.3
−3	12	1.84
−2	98	15.07
−1	174	26.76
0	256	39.38
1	94	14.46
2	13	2
3	1	0.15

Table 3
shows the numerical results for the whole region.

Value	Count	Percentage (%)	Surface (ha)
0	24710402	//	2223936
2	474	0.466311	42.66
3	88736	87.29648	7986.24
4	12439	12.23721	1119.51

Table 3. Result of the street tree NbS suitability analysis. Only pixel containing streets are considered. Pixels classified as 0 represent areas with no street network.

results). While urban and peri-urban areas are strongly connected with the cities and their surroundings, numerous agricultural areas are also situated in the southern hilly region, although their classification is typically 3 or lower.

According to the results, buffer strips can be located everywhere in the region, except for some steep areas in the hilly southern part of Emilia-Romagna and in the immediate proximity of the main urban centres, where agricultural areas are lacking. Even in this case, the most suitable areas are predominantly located in the northern part of the region, apart from the major cities.

These results provide good suggestions for the best locations for strategic carbon sequestration NbS implemented in urban, peri-urban, and agricultural areas. The GIS-based multicriteria land suitability assessment model developed and tested in this study offers a novel

approach to addressing the NbS location problem, particularly for street trees and buffer strips.

3.2. Sensitivity analysis

The sensitivity analysis (SA) is a useful tool to test the robustness of the final outcome (Zoras et al., 2007). This analysis aims to adjust the initial weighting parameters to evaluate how changes influence the model outputs. By comparing the modified results with the original outcomes, the adequacy of the weight assignments can be assessed and identify potential biases (Watson and Hudson, 2015). This process when conducting a GIS-MCDA (Ishizaka and Labib, 2011) can facilitate the evaluation of outcomes derived from subjectively assigned weights. Although the inherent subjectivity in the Weighting Linear Combination method cannot be completely eliminated, this sensitivity analysis provides a systematic approach for identifying and mitigating potential errors (Mészáros and Rapcsák, 1996).

Some examples can be found in Amsharuk and Łaska, (2023), where the authors applied the SA on a GIS-MCDA study for finding the best location for wind farms in Podlaskie Voivodeship, Poland. Another one is in Nisyak et al., (2017) where they used the SA to validate the result of a GIS-MCDA applied on a rice field suitability analysis in Batu City, Indonesia. Roy et al. (2022) described the use of the SA used on a GIS-MCDA work on the most suitable areas for a landfill in West Bengal, India. Another case is by Shorabeh et al. (2019) who analysed the solar power plant site selection in different climates in four provinces of Iran. Finally, Zaniboni et al. (2024) applied the SA on a GIS-MDCA study about the most suitable location of integrated multi-trophic aquaponic systems in Emilia-Romagna.

The SA was conducted using a one-at-a-time approach, where the weights of each criterion were gradually increased while proportionally decreasing the weights of all other parameters. This method enables the assessment of the significance of each factor individually (Malczewski and Rinner, 2015). Specifically, the weights of each criterion were incremented by 1 % at a time, up to a total of 20 %. To proof the robustness of the model, the results expected from the sensitivity analyses are an increment of the high-class pixels for the most important criteria as the weight is increasing towards 20 % and a decrease of the
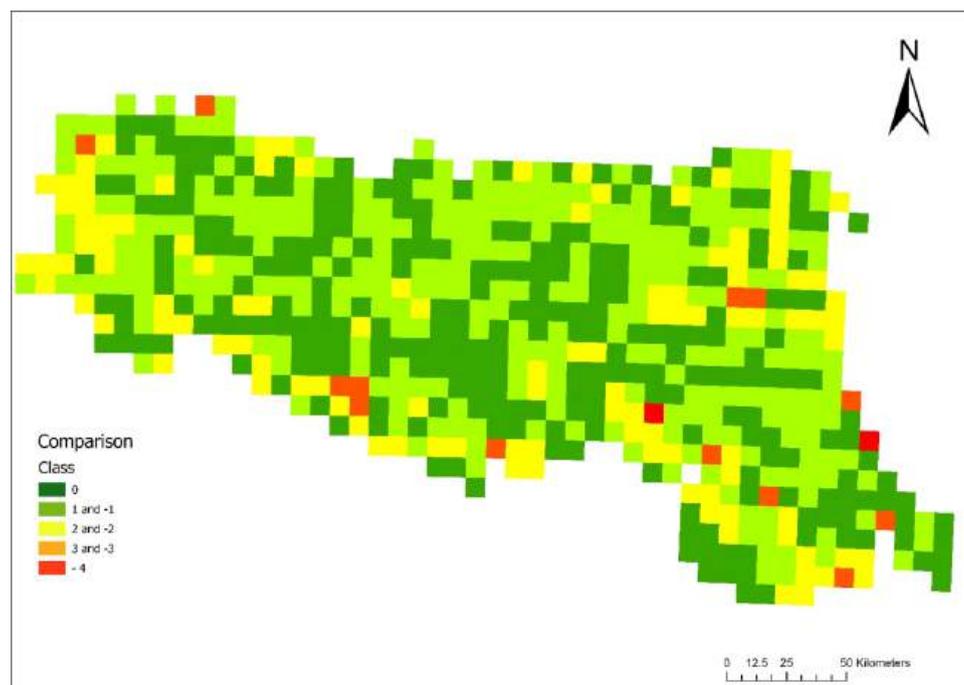

Fig. 6. Comparison between the two models. The greener the more the two models are comparable, the redder the more the two models differ.
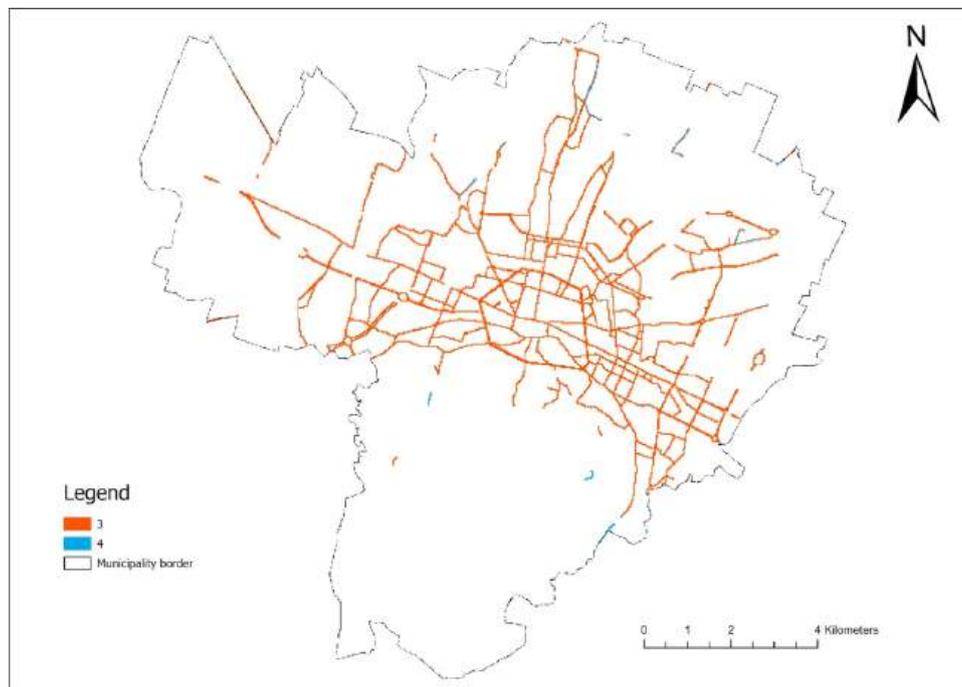
Fig. 7. Result of the suitability analysis on the territory of the municipality of Bologna for the street tree NbS (urban areas). Only the coloured pixels are eligible for the street tree NbS. The ones depicted in orange are classified as averagely suitable for hosting the NbS, the ones depicted in blue are classified as highly suitable.
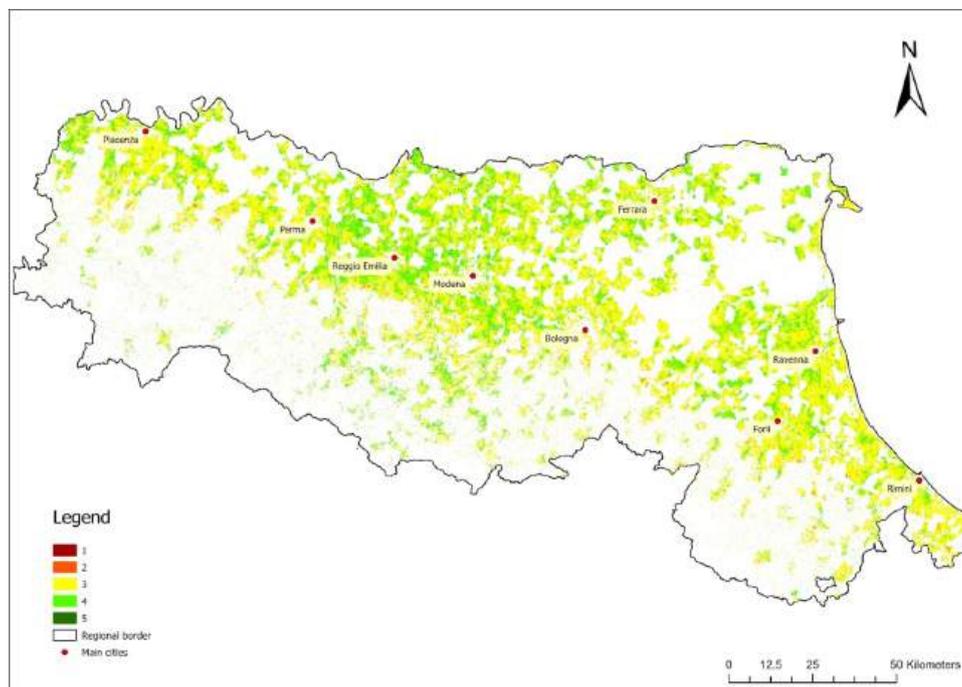

Fig. 8. Result of the suitability analysis for the green space NbS (peri-urban areas). Only the coloured pixels are eligible for the green space NbS. The greener the better the suitability for this specific NbS.

low-class pixels for the least important criteria. A high-class pixel refers to pixels classified as highly suitable, specifically those assigned a value of 4 or 5. On the other hand, a low-class pixel refers to pixels classified as less suitable, specifically those assigned a value of 1 or 2. A different one-at-a-time SA was performed on the three different GIS-MCDA analysis. A total of 380 cases have been studied (100 for the street tree NbS, 140 for the green space NbS and 140 for the buffer strip NbS). For every run, changes in quantity for every pixel class were tracked, as

it is shown in Table 6, which is an example of the 19 tables created (one for each criterion) showing the modifications of criterion.

1) Street trees

Table 6 represents the changes in quantity of pixels belonging to a class (columns) for the street trees NbS after every percentage increase of the "Carbon emission" criterion (rows). Only the "Carbon emission"

Table 4
Result of the green spaces NbS suitability analysis.

Class	Count of suitability map of street trees in urban areas	Percentage (%)	Surface of suitability map (ha)
0	17575971	//	1581837
1	2346	0.03	211.86
2	49904	0.68	4506.48
3	4958293	67.49	447751.1
4	2326839	31.67	210121.7
5	9273	0.13	837.36

Table 5
Result of the buffer strip NbS suitability analysis.

Class	Count of suitability map of street trees in urban areas	Percentage (%)	Surface of suitability map (ha)
0	16376710	//	1473904
1	666	0.007897986	59.94
2	392381	4.65318293	35314.29
3	2996755	35.53803373	269708
4	5025466	59.59618994	452291.9
5	17261	0.204695412	1553.49

criterion is presented in this table since it was considered as the most important one for the aim of the suitability analysis. This and all the other criteria will be also represented in the picture format later in this paragraph. The suitability analysis row represents the values after the GIS-MCDA.

The row labelled "Suitability Analysis" shows the results of the suitability analysis, with values matching those in Table 3 under the "Count " column.

The row labelled "1 %" represents the scenario where the weight of the "Carbon emissions" criterion is increased by 1 %. Each subsequent row shows the results of further increasing this weight, up to 20 %. While the weight of carbon emissions increases, the distribution of areas across the different suitability classes (1 to 5) changes. Specifically, some classes see an increase in the number of areas they cover, while others see a decrease, reflecting how more emphasis on carbon emissions influences the overall suitability outcomes.

Fig. 10 illustrates the changes in the number of pixels in class 4 (the highest, none of the pixels is classified as class 5, even after increasing of 20 % in importance) for the 5 criteria of the street tree NbS.

The carbon emission criterion is the most sensitive, meaning that it has the greatest impact on the results, followed by the temperature criterion and the wind strength criterion. The parameters that have a minor impact on the results are the solar radiation and the precipitation. These results are consistent with the expectations.

The numerical values of the previous graphs are presented in Table 7,

Table 6
Changes in quantity of pixels belonging to a class (columns) for the street trees NbS after every percentage increase of the "Carbon emission" criterion (rows). Suitability analysis row represents the values after the GIS-MCDA.

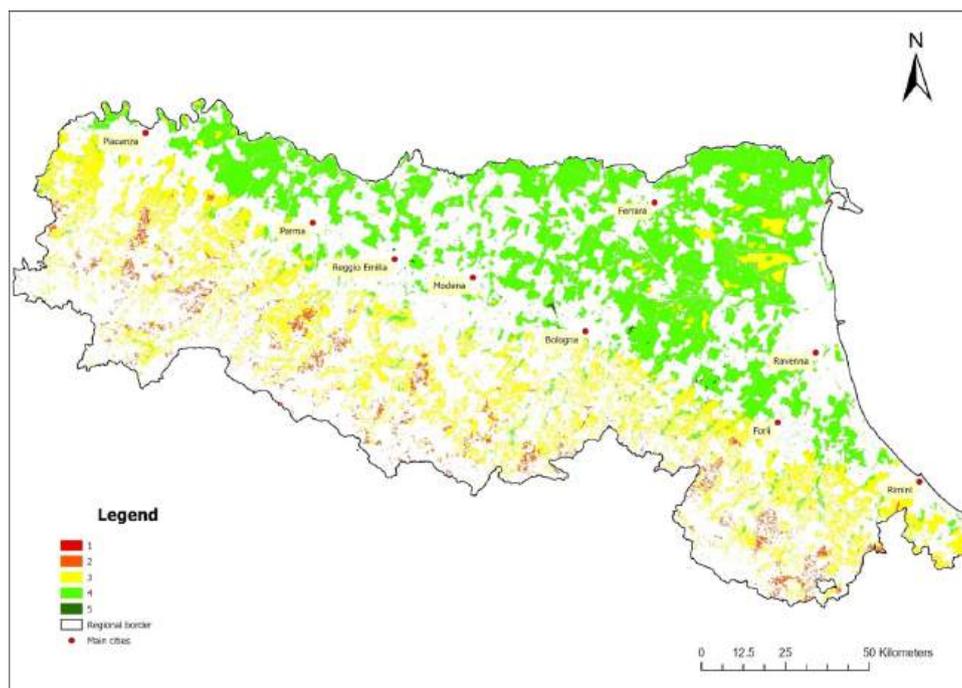|	1	2	3	4	5
Suitability analysis	0	474	88736	12439	0
1 %	0	51	61255	40343	0
2 %	0	51	60903	40695	0
3 %	0	51	60903	40695	0
4 %	0	51	40555	61043	0
5 %	0	83	40179	61387	0
6 %	0	83	40179	61387	0
7 %	0	170	40060	61419	0
8 %	0	170	40060	61419	0
9 %	0	170	39953	61526	0
10 %	0	170	39953	61526	0
11 %	0	170	34279	67200	0
12 %	0	241	34007	67401	0
13 %	0	241	34003	67405	0
14 %	0	241	34003	67405	0
15 %	0	241	34003	67405	0
16 %	0	241	31096	70312	0
17 %	0	246	30053	71350	0
18 %	0	246	29663	71740	0
19 %	0	246	29663	71740	0
20 %	0	246	29663	71740	0

Fig. 9. Result of the suitability analysis for the buffer strips NbS (agricultural areas). Only the coloured pixels are eligible for the buffer strips NbS. The greener the better the suitability for this specific NbS.
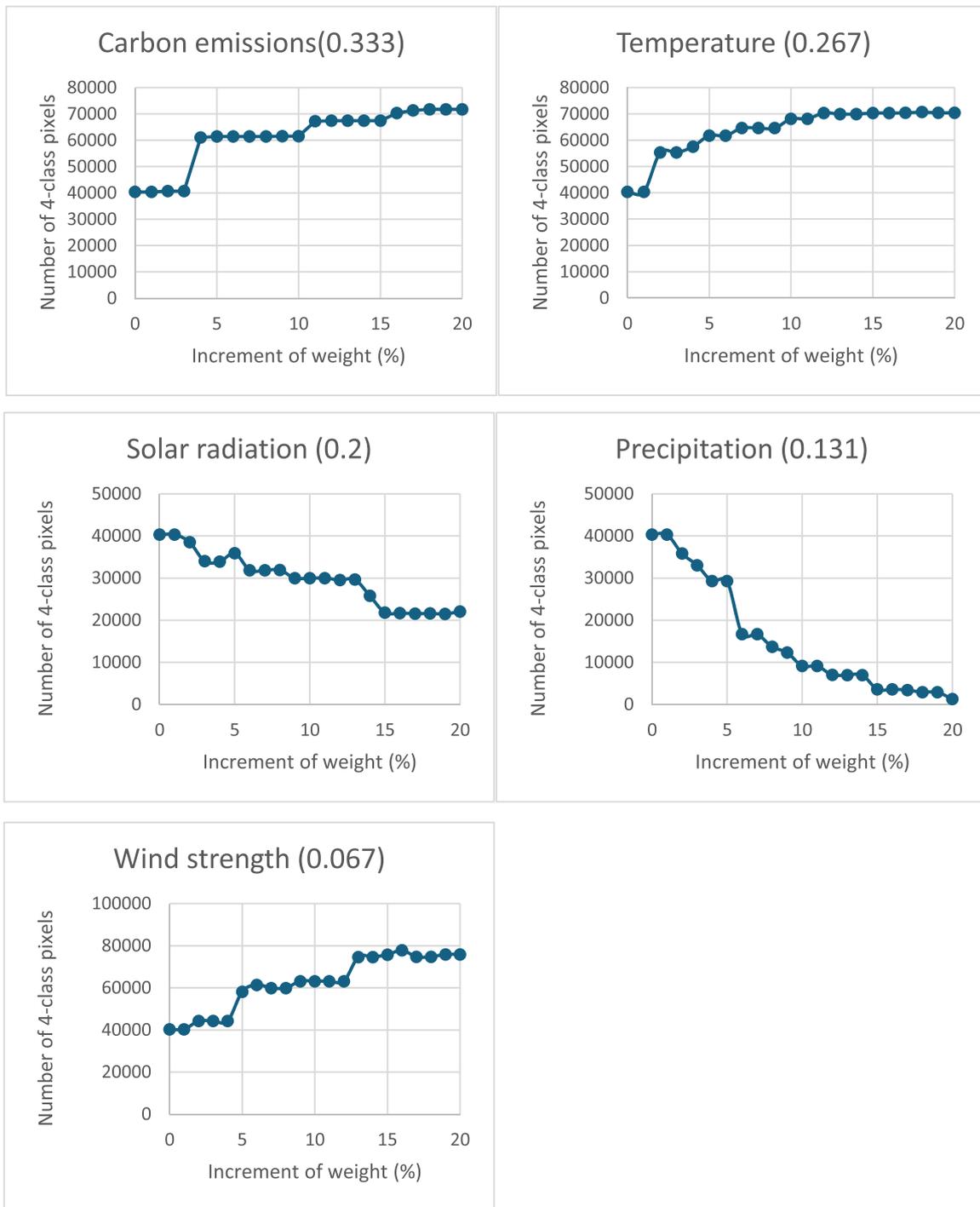
Fig. 10. Graphs of the changes in 4-class pixels after every increment of weights.

showing a comparison between the initial and final counts of high-class pixels.

2) Green space NbS

As in the case of the street trees NbS, Table 8 represents the changes in quantity of pixels belonging to a class (columns) in "Slope" criterion for the green space NbS and after every percentage increase (rows). Only the "Slope" criterion is presented in this table since it was considered as the most important one for the aim of the suitability analysis.

As it can be noted, the number of high-class pixels increases, while the number of low-class pixels decreases.

Fig. 11 illustrates the changes in the number of pixels in class 5 for the 7 criteria of the green area NbS.

The third column represents the count of 4-class pixels after the GIS-MCDA and before the starting of the SA. The fourth column represents the count of 4-classes at the end of the SA. The sixth and seventh columns represent the same for the 4-class pixels. The most important column is the rightmost one, which includes the sum of the two comparison columns, indicating the total number of high-class pixels for each criterion after a 20 % weight increment. As expected, among the most sensitive criterion there is the carbon emission that shows a remarkable increasing in 4-class pixels. Also, the slope and the accessibility produce a strong impact on the results, while the less sensitive

Table 7

Counts of high-class pixels for the initial and final run for each criterion in the street tree NbS suitability analysis.

Importance ranking	Criteria	Initial count of 4-class pixels	Count of 4-class pixels after 20 % weight increment	Comparison of class-4 pixels (final count-initial count)
1	Carbon emissions	12439	71740	59301
2	Temperature	12439	70403	57964
3	Solar radiation	12439	22064	9625
4	Precipitation	12439	1270	−11169
5	Wind strength	12439	75899	63460

Table 8

Changes in quantity of pixels belonging to a class (columns) for the street trees NbS after every percentage increase of the "Slope" criterion (rows). Suitability analysis row represents the values after the GIS-MCDA.

	1	2	3	4	5
Suitability analysis	2346	49904	4958293	2326839	9273
1 %	379	46469	4821792	2469964	8051
2 %	379	41885	4635583	2660757	8051
3 %	379	41543	4635937	2660745	8051
4 %	379	39432	4348329	2950464	8051
5 %	404	38381	4193445	3106317	8108
6 %	419	39113	4168401	3130055	8667
7 %	419	39070	4005198	3293301	8667
8 %	419	38671	3771734	3527164	8667
9 %	419	38568	3767535	3531466	8667
10 %	436	35625	3427884	3873476	9234
11 %	436	35422	3218303	4083260	9234
12 %	436	35406	3040318	4261261	9234
13 %	436	35713	2944944	4356328	9234
14 %	461	35634	2796053	4494816	19691
15 %	461	36054	2620660	4669789	19691
16 %	461	36008	2389595	4900900	19691
17 %	515	36220	2042375	5243426	24119
18 %	515	36292	1865949	5419780	24119
19 %	515	36527	1760397	5525097	24119
20 %	640	38749	1678810	5598255	30201

criteria are the residential object density and the land cover.

3) Buffer strip NbS

Table 10 represents the changes in quantity of pixels belonging to a class (columns) in the "Carbon emissions" criterion and after every percentage increase (rows), which has been identified as the most sensitive one. Only the "Carbon emission" criterion is presented in this table since it was considered as the most important one for the aim of the suitability analysis.

In this case, there is a substantial stability: both low-class and high-class pixels slightly decrease, while the only class that increases is class 3.

Fig. 12 illustrates the changes in the number of pixels in class 5 for the 7 criteria of the buffer strip NbS.

As the previous case, the most important column is the rightmost one. This column shows the sum of the two comparison columns, representing the total number of high-class pixels for each criterion after a 20 % weight increase. The most sensitive criteria are the proximity to water bodies and the precipitation, while the least sensitive are the solar radiation and the carbon emissions. This is particularly interesting because, in the other two cases, carbon emissions are a highly sensitive parameter. This can be explained by considering that agricultural areas are typically less affected by carbon emission and are usually located far from carbon sources. As a result, carbon emissions have a weaker influence on the outcomes compared to the other two cases.

3.3. Carbon sequestration calculation

The carbon sequestration calculation estimates the potential quantity of carbon that can be sequestered by the proposed NbS. This calculation assumes that a new NbS would be located in every high-class pixel (classes 5) identified in the suitability analyses. Therefore, even if only a single NbS were implemented in the highlighted areas, it would still significantly contribute to reducing atmospheric carbon levels and enhancing the liveability of urban, peri-urban, or agricultural areas. This approach provides an indication of the overall potential effectiveness in carbon sequestration of the NbS strategies under study.

1) Street trees

Fig. 13 represents the street trees expected from the suitability analysis compared to those already present.

In this case, since none of the pixel is classified with class 5, pixels of class 4 were considered. The number of class-4 pixels predicted by the suitability analysis, where street trees are not already present, is 167. Based on the processes described in paragraph 2.8, a total of 30.113 tons of carbon can be sequestered annually in the municipality of Bologna alone.

2) Green spaces
   The total amount of carbon that can be sequestered in the entire Emilia-Romagna region, if green spaces were located in all the 5-class pixels (only in peri-urban areas), would be 1870.662 tons per year.
3) Buffer strips

The total amount of carbon that can be sequestered in the entire territory of Emilia-Romagna, if buffer strip NbS based on silver poplars were located in all the 5-class pixels, would be 2291.398 tons per year.
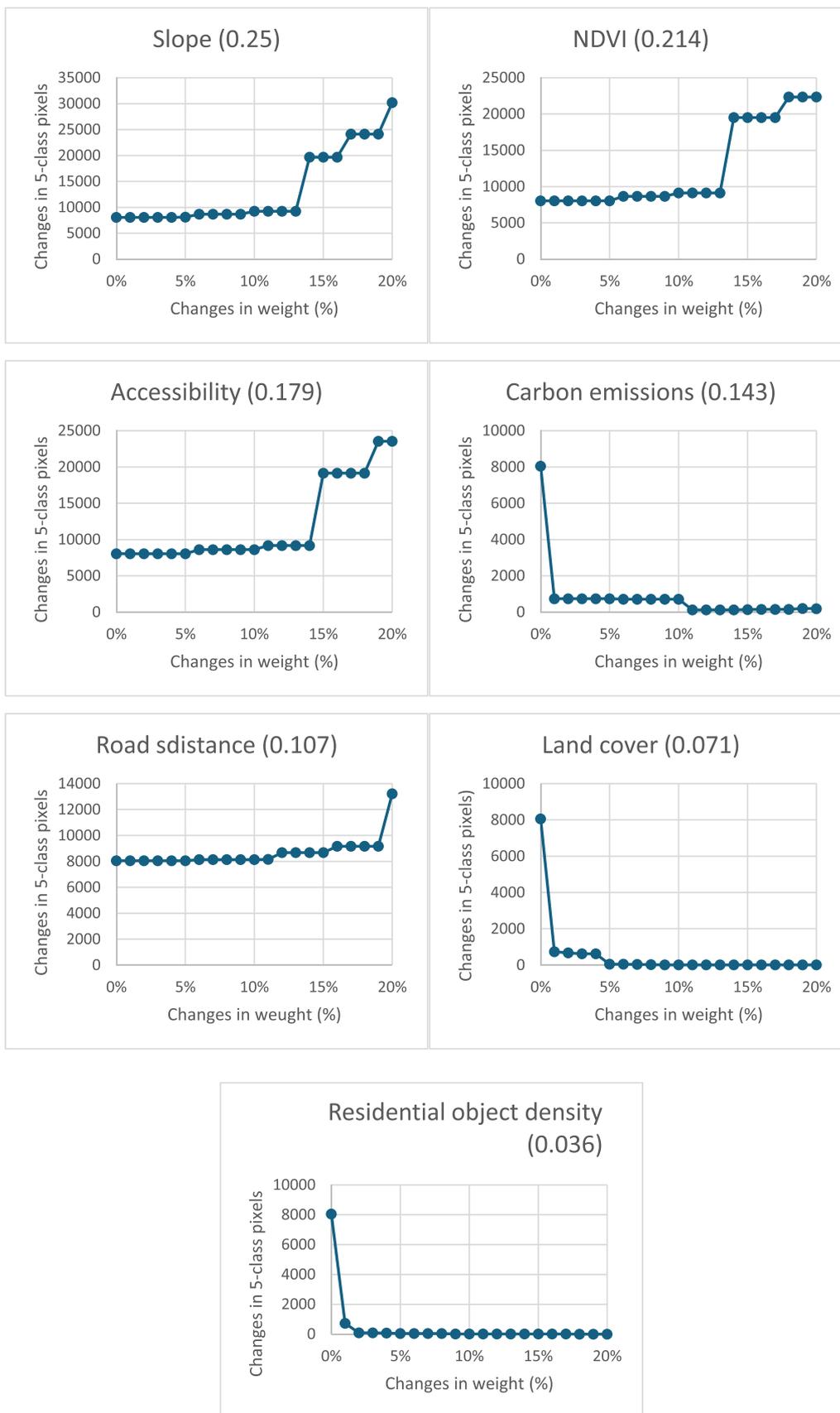
Table 9

presents a comparison between the initial and final counts of high-class pixels.

Importance ranking	Criteria	Initial count of 4-class pixels	Count of 4-class pixels after 20 % weight increment	Comparison of class-4 pixels (final count-initial count)	Initial count of 5-class pixels	Count of 5-class pixels after 20 % weight increment	Comparison of class-5 pixels (final count-initial count)	Sum of 4-class and 5-class comparison
1	Slope	2326839	5598255	3271416	9273	30201	20928	3292344
2	NDVI	2326839	1856511	−470328	9273	22342	13069	−457259
3	Accessibility	2326839	3231014	904175	9273	23543	14270	918445
4	Carbon emission	2326839	3016505	689666	9273	193	−9080	680586
5	Road distance	2326839	2261687	−65152	9273	13214	3941	−61211
6	Land cover	2326839	536394	−1790445	9273	9	−9264	−1799709
7	Residential object density	2326839	151839	−2175000	9273	1	−9272	−2184272

Table 9. Counts of high-class pixels for the initial and final run for each criterion in the green space NbS suitability analysis.

Fig. 11. Graphs of the changes in 5-class pixels after every increment of weights.

Table 10

Changes in quantity of pixels belonging to a class (columns) for the street trees NbS after every percentage increase of the "Carbon emission" criterion (rows). Suitability analysis row represents the values after the GIS-MCDA.

	1	2	3	4	5
Suitability analysis	480	377852	3008692	5028030	17475
1 %	577	358003	3036056	5034007	3886
2 %	577	356933	3037440	5033693	3886
3 %	577	356933	3038773	5032360	3886
4 %	577	356890	3039267	5031909	3886
5 %	577	359032	3050867	5018164	3889
6 %	309	320968	3264445	4844307	2500
7 %	309	319705	3265575	4844440	2500
8 %	309	319799	3266560	4843361	2500
9 %	309	319799	3266560	4843361	2500
10 %	429	276826	3309443	4843297	2534
11 %	429	276548	3309792	4843226	2534
12 %	429	276583	3309757	4843226	2534
13 %	429	276482	3312640	4840444	2534
14 %	451	270860	3254964	4901296	4958
15 %	451	270869	3254957	4901294	4958
16 %	451	270592	3256027	4900501	4958
17 %	517	242415	3351810	4832297	5490
18 %	517	242417	3351808	4832297	5490
19 %	517	242568	3351626	4832328	5490
20 %	528	220631	3423657	4781672	6041

It is notable to remind that 5-class pixels are generally quite uncommon. The peri-urban areas covered by these pixels only account for 837.36 ha, while the agricultural areas covered by 5-class pixels occupy 1553.49 ha. For comparative purposes, Emilia-Romagna has a total surface of 2245,100 ha.

4. Conclusions

The principal objective of this study was to identify the most suitable locations for implementing various Nature-based Solutions (NbS) to optimise carbon sequestration. Overall, the research identified that street trees are the most effective NbS for carbon sequestration in urban environments, green spaces for peri-urban areas and buffer strips for agricultural zones.

In addition, the study resulted in the following specific conclusions:

First, the GIS-MCDA methodology, though widely used in different sectors concerning NBS, has had limited application in the context of street trees and buffer strips, which this study sought to address.

Secondly, the results for street trees provide valuable insights into the potential of NbS, despite being limited by the small number of pixels representing the urban environment. The study highlights that street trees in Bologna alone could sequester up to 30 tons of carbon annually, which represents a significant potential contribution to carbon reduction. Additionally, the study emphasises the wide range of additional benefits of street trees, including enhanced urban liveability, improved

air quality, reduced stormwater runoff, habitat connectivity and social benefits like increased community safety and improved property values. This NbS can also contribute to further emissions reduction in the urban context via indirect mechanisms such as microclimate regulation and encouraging a behavioural shift by residents towards non-motorised transport (Pan et al., 2023).

Third, for peri-urban areas, green spaces were found to be most suitable for carbon sequestration, especially in flat northern regions and areas close to coastlines. Implementing green spaces in areas classified as class 5 pixels could result in an estimated carbon sequestration of 1870 tons per year, with even higher potential if class 4 pixels are included.

Fourth, buffer strips were identified as highly suitable for implementation in areas throughout the region, excluding some steep southern areas and zones close to major urban centres. Implementing buffer strips in areas classified as class 5 pixels could lead to carbon sequestration of approximately 2291 tons annually.

Fifth, the study used a comprehensive literature review to identify appropriate criteria and weights for the GIS-MCDA methodology. Sensitivity analysis results contributed to refine the importance of these criteria, further enhancing the study's outcomes.

Sixth, the findings provide valuable data to guide decision-makers and urban planners in selecting the most suitable locations for NBS implementation, specifically focused on carbon sequestration. Additionally, the study highlights key areas where NbS should be prioritised to maximise carbon sequestration and simplify decision-making processes by specifying the most effective NbS for each location.

This study provides an initial estimate of the environmental benefits that could be achieved by implementing NbS in high-priority areas, but further research is needed for more detailed calculations to increase accuracy and enhance findings. While this study focused on the Emilia-Romagna region, the methodology can be extended to other areas with consideration for local parameters, such as tree species selection and planning provisions from municipalities. Future research could integrate these aspects to ensure consistency and methodological homogeneity for specific NbS planning goals. Moreover, future research should aim at a more in-depth assessment of carbon sequestration potential by the studied NbS. While carbon sequestration assessment was not the main focus of this study, further research could develop more accurate estimates through modelling and simulation approaches, providing deeper insights into the environmental impact of NbS.

CRediT authorship contribution statement

Berit Balfors: Writing – review & editing, Supervision, Methodology. **Andrea Zaniboni:** Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Zahra Kalantari:** Writing – review & editing, Supervision, Methodology. **Daniele Torreggiani:** Writing –
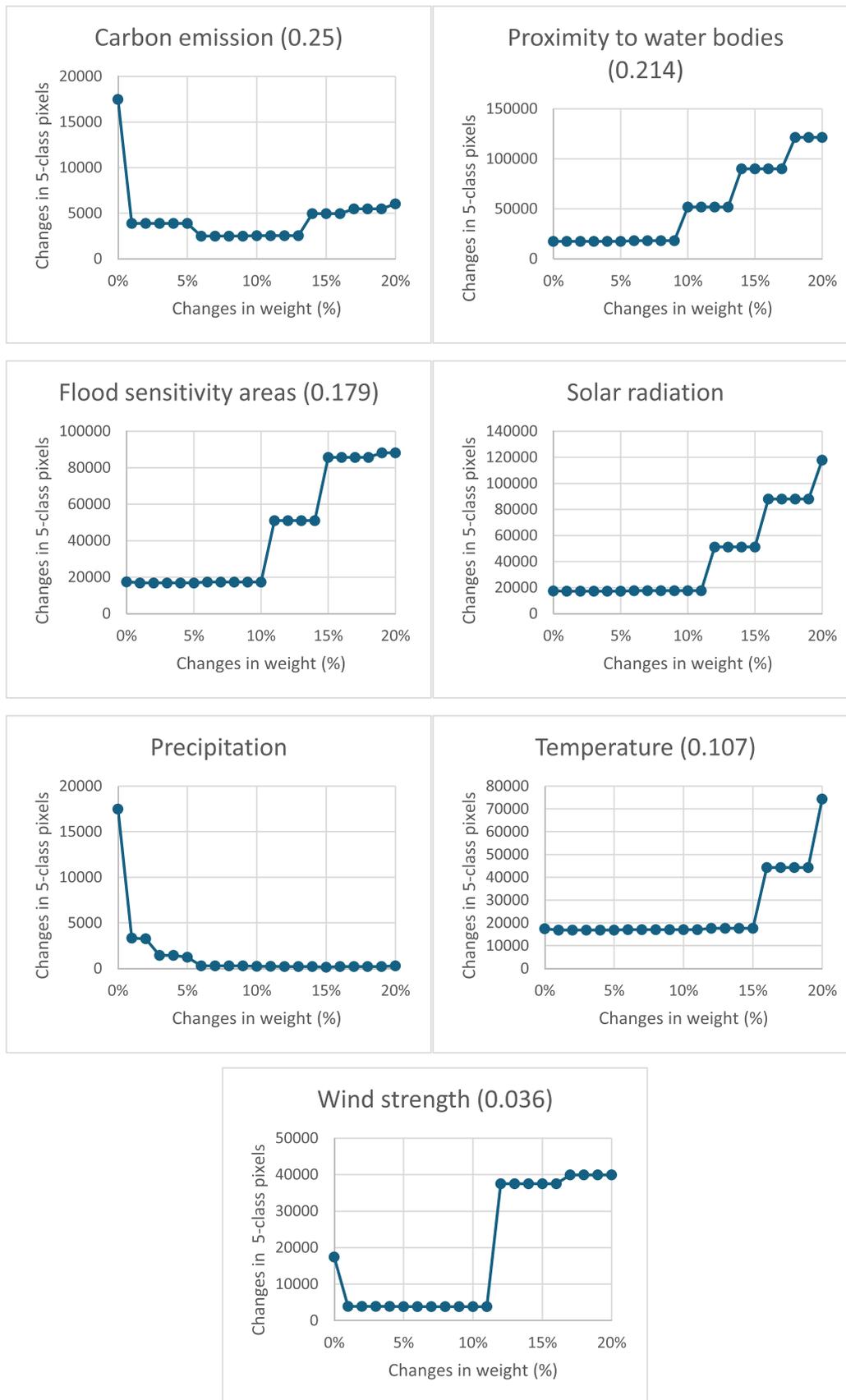
Table 11

presents a comparison between the initial and final counts of high-class pixels.

Importance ranking	Criteria	Initial count of 4-class pixels	Count of 4-class pixels after 20 % weight increment	Comparison of class-4 pixels (final count- initial count)	Initial count of 5-class pixels	Count of 5-class pixels after 20 % weight increment	Comparison of class-5 pixels (final count- initial count)	Sum of 4-class and 5-class comparison
1	Carbon emissions	5028030	4781672	−246358	17475	6041	−11434	−257792
2	Proximity to water bodies	5028030	5517989	489959	17475	121464	103989	593948
3	Flood sensitivity areas	5028030	4819011	−209019	17475	88200	70725	−138294
4	Precipitation	5028030	5469315	441285	17475	117955	100480	541765
5	Solar radiation	5028030	2501845	−2526185	17475	282	−17193	−2543378
6	Temperature	5028030	5462571	434541	17475	74282	56807	491348
7	Wind strength	5028030	5409889	381859	17475	39934	22459	404318

Table 11. Counts of high-class pixels for the initial and final run for each criterion in the buffer strip NbS suitability analysis.

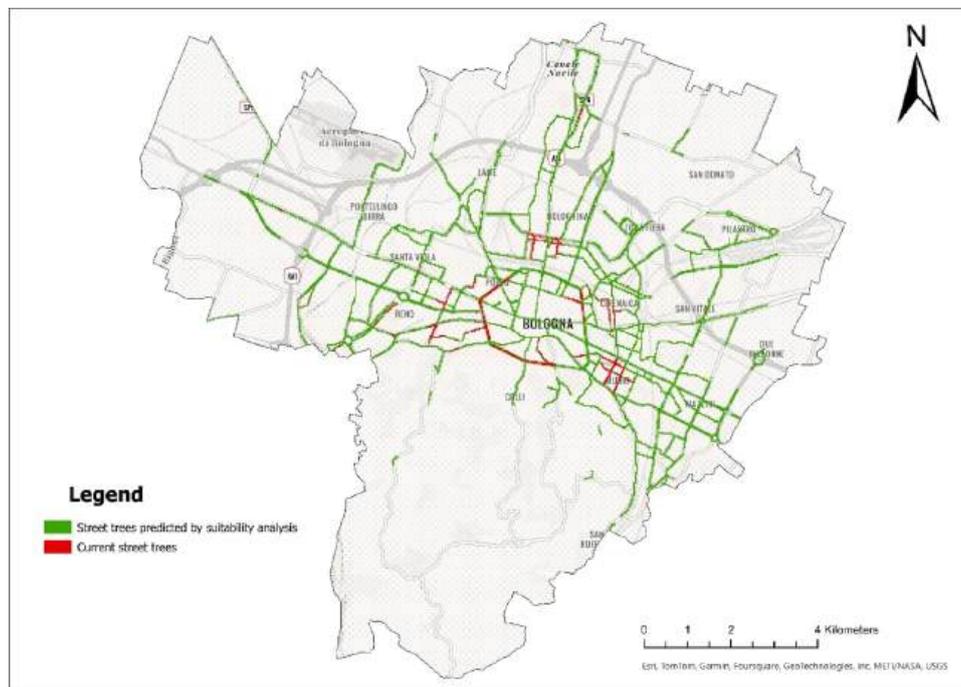**Fig. 12.** Graphs of the changes in 4-class pixels after every increment of weights.

Fig. 13. Existing street trees and street trees in suitable places in the municipality of Bologna. Green areas indicate locations recommended for tree planting based on this study, while red areas represent locations where street trees are already present.

review & editing, Writing – original draft, Validation, Supervision, Software, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Patrizia Tassinari:** Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition. **Jessica Page:** Writing – review & editing, Supervision, Methodology.

Declaration of Competing Interest

Acknowledgements

Data Availability

Data will be made available on request.

References

Abebe, M.T., Megento, T.L., 2017. Urban green space development using GIS-based multi-criteria analysis in Addis Ababa metropolis. Appl. Geomat. 9 (4), 247–261. https://doi.org/10.1007/s12518-017-0198-7.

Agostini, C., Bellodi, S., Cantini, M., Foscoli, D., Maccaferri, S., Manzini, M.E., Marinello, S., Pironi, C., & Rumberti, V. 2024. Aggiornamento dell'inventario regionale delle emissioni in atmosfera dell'emilia-romagna relativo all'anno 2021.

Alves, A., Gersonius, B., Kapelan, Z., Vojinovic, Z., Sanchez Torres, A., 2019. Assessing the Co-Benefits of green-blue-grey infrastructure for sustainable urban flood risk management. J. Environ. Manag. 239, 244–254. https://doi.org/10.1016/j.jenvman.2019.03.036.

Amsharuk, A., Łaska, G., 2023. The approach to finding locations for wind farms using GIS and MCDA: case study based on Podlaskie Voivodeship, Poland. Energies 16 (20). https://doi.org/10.3390/en16207107.

Aram, F., Higueras García, E., Solgi, E., Mansournia, S., 2019. Urban green space cooling effect in cities. Heliyon 5 (4), e01339. https://doi.org/10.1016/j.heliyon.2019.e01339.

Aronson, M.F.J., Lepczyk, C.A., Evans, K.L., Goddard, M.A., Lerman, S.B., MacIvor, J.S., Nilon, C.H., Vargo, T., 2017. Biodiversity in the city: key challenges for urban green space management. Front. Ecol. Environ. 15 (4), 189–196. https://doi.org/10.1002/fee.1480.

Bailey, N.J., Motavalli, P.P., Udawatta, R.P., Nelson, K.A., 2009. Soil CO2 emissions in agricultural watersheds with agroforestry and grass contour buffer strips. Agrofor. Syst. 77 (2), 143–158. https://doi.org/10.1007/s10457-009-9218-x.

Baldocchi, D.D., Ma, S., Rambal, S., Misson, L., Ourcival, J.-M., Limousin, J.-M., Pereira, J., Papale, D., 2010. On the differential advantages of evergreenness and deciduousness in mediterranean oak woodlands: a flux perspective. Ecol. Appl. 20 (6), 1583–1597. https://doi.org/10.1890/08-2047.1.

Barati, A.A., Zhoolideh, M., Azadi, H., Lee, J.-H., Scheffran, J., 2023. Interactions of land-use cover and climate change at global level: How to mitigate the environmental risks and warming effects. Ecol. Indic. 146, 109829. https://doi.org/10.1016/j.ecolind.2022.109829.

Beketie, K.T., Angessa, A.T., Zeleke, T.T., Ayal, D.Y., 2022. Impact of cement factory emission on air quality and human health around Mugher and the surrounding villages, Central Ethiopia. Air Qual. Atmosph. Health 15 (2), 347–361. https://doi.org/10.1007/s11869-021-01109-4.

Bičík, I., Kupková, L., & Stych, P. 2012. Changes of Land Use Structure in Czechia: From Local Patterns to a More Complex Regional Organization. ⟨www.lucc.ic.cz⟩.

Borin, M., Vianello, M., Morari, F., Zanin, G., 2005. Effectiveness of buffer strips in removing pollutants in runoff from a cultivated field in North-East Italy. Agric., Ecosyst. Environ. 105 (1), 101–114. https://doi.org/10.1016/j.agee.2004.05.011.

Carnevale, C., Finzi, G., Pederzoli, A., Pisoni, E., Thunis, P., Turrini, E., Volta, M., 2015. A methodology for the evaluation of re-analyzed PM10 concentration fields: a case study over the PO Valley. Air Quality, Atmosphere & Health 8 (6), 533–544. https://doi.org/10.1007/s11869-014-0307-2.

Castro, C.V., Rifai, H.S., 2021. Development and assessment of a web-based national spatial data infrastructure for nature-based solutions and their social, hydrological, ecological, and environmental co-benefits. Sustainability 13 (19). https://doi.org/10.3390/su131911018.

Çetinkaya, C., Özceylan, E., Erbaş, M., Kabak, M., 2016. GIS-based fuzzy MCDA approach for siting refugee camp: a case study for southeastern Turkey. Int. J. Disaster Risk Reduct. 18, 218–231. https://doi.org/10.1016/j.ijdrr.2016.07.004.

Chunyang Zhu, P.J., Li, S., 2017. Effects of urban green belts on the air temperature, humidity and air quality. J. Environ. Eng. Landsc. Manag. 25 (1), 39–55. https://doi.org/10.3846/16486897.2016.1194276.

Church, R.L., 2002. Geographical information systems and location science. Comput. Oper. Res. 29 (6), 541–562. https://doi.org/10.1016/S0305-0548(99)00104-5.

Cole, L.J., Stockan, J., Helliwell, R., 2020. Managing riparian buffer strips to optimise ecosystem services: a review. Agric., Ecosyst. Environ. 296, 106891. https://doi.org/10.1016/j.agee.2020.106891.

Commission, E., Agency, E.R.E., 2023. Nature-based solutions – EU-funded nbs research projects tackle the climate and biodiversity crisis. Publ. Off. Eur. Union. https://doi.org/10.2848/8542246.

Cong, C., Pan, H., Page, J., Barthel, S., Kalantari, Z., 2023. Modeling place-based nature-based solutions to promote urban carbon neutrality. Ambio 52 (8), 1297–1313. https://doi.org/10.1007/s13280-023-01872-x.

Dana Tomlin, C. (1990). Geographic Information Systems and Cartographic Modeling.

Dong, S., Ma, J., Mo, Y., Yang, H., 2022. GIS-based watershed unit forest landscape visual quality assessment in Yangshuo section of Lijiang River Basin, China. Sustainability 14 (22). https://doi.org/10.3390/su142214895.

Dunn, R.M., Hawkins, J.M.B., Blackwell, M.S.A., Zhang, Y., Collins, A.L., 2022. Impacts of different vegetation in riparian buffer strips on runoff and sediment loss. Hydrol. Process. 36 (11). https://doi.org/10.1002/hyp.14733.

Duvillard, P.-A., Ravanel, L., Deline, P., 2015. Risk assessment of infrastructure destabilisation due to global warming in the high French Alps. Rev. De. Géograph. Alp. https://doi.org/10.4000/rga.2896.

van Eupen, M., Metzger, M.J., Pérez-Soba, M., Verburg, P.H., van Doorn, A., Bunce, R.G.H., 2012. A rural typology for strategic European policies. Land Use Policy 29 (3), 473–482. https://doi.org/10.1016/j.landusepol.2011.07.007.

Fang, X., Li, J., Ma, Q., Zhou, R., Du, S., 2024. A quantitative review of nature-based solutions for urban sustainability (2016–2022): from science to implementation. Sci. Total Environ. 927, 172219. https://doi.org/10.1016/j.scitotenv.2024.172219.

Fang, L., Wang, Y., 2018. Multi-disciplinary determination of the rural/urban boundary: a case study in Xi'an, China. Sustainability 10 (8). https://doi.org/10.3390/su10082632.

Fiorani, F., & Punzo, L. 2021. Alberi per la città - Un abaco per l'infrastruttura verde urbana.

Fortier, J., Gagnon, D., Truax, B., Lambert, F., 2010. Nutrient accumulation and carbon sequestration in 6-year-old hybrid poplars in multiclonal agricultural riparian buffer strips. Agric. Ecosyst. Environ. 276–287. https://doi.org/10.1016/j.agee.2010.02.013.

Gelan, E., 2021. GIS-based multi-criteria analysis for sustainable urban green spaces planning in emerging towns of Ethiopia: the case of Sululta town. Environ. Syst. Res. 10 (1), 13. https://doi.org/10.1186/s40068-021-00220-w.

Ghassemi Nejad, J., Ju, M.-S., Jo, J.-H., Oh, K.-H., Lee, Y.-S., Lee, S.-D., Kim, E.-J., Roh, S., Lee, H.-G., 2024. Advances in methane emission estimation in livestock: a review of data collection methods, model development and the role of AI technologies. Animals 14 (3). https://doi.org/10.3390/ani14030435.

Gonçalves, J., Gomes, M.C., Ezequiel, S., Moreira, F., Loupa-Ramos, I., 2017. Differentiating peri-urban areas: a transdisciplinary approach towards a typology. Land Use Policy 63, 331–341. https://doi.org/10.1016/j.landusepol.2017.01.041.

Gottero, E., Larcher, F., Cassatella, C., 2023. Defining and regulating peri-urban areas through a landscape planning approach: the case study of Turin Metropolitan Area (Italy). Land 12 (1). https://doi.org/10.3390/land12010217.

Han, A.T., Daniels, T.L., Kim, C., 2022. Managing urban growth in the wake of climate change: Revisiting greenbelt policy in the US. Land Use Policy 112, 105867. https://doi.org/10.1016/j.landusepol.2021.105867.

Hansen, Sato, M., Hearty, P., Ruedy, R., Kelley, M., Masson-Delmotte, V., Russell, G., Tselioudis, G., Cao, J., Rignot, E., Velicogna, I., Kandiano, E., Schuckmann, K., Kharecha, P., LeGrande, A., Bauer, M., Lo, K., 2015. Ice melt, sea level rise and superstorms: evidence from paleoclimate data, climate modeling, and modern observations that 2°C global warming is highly dangerous. Atmos. Chem. Phys. Discuss. 15, 20059–20179. https://doi.org/10.5194/acpd-15-20059-2015.

Huang, Y., Krigsvoll, G., Johansen, F., Liu, Y., Zhang, X., 2018. Carbon emission of global construction sector. Renew. Sustain. Energy Rev. 81, 1906–1916. https://doi.org/10.1016/j.rser.2017.06.001.

Hussain, S., Mubeen, M., Akram, W., Ahmad, A., Habib-ur-Rahman, M., Ghaffar, A., Amin, A., Awais, M., Farid, H.U., Farooq, A., Nasim, W., 2019. Study of land cover/land use changes using RS and GIS: a case study of Multan district, Pakistan. Environ. Monit. Assess. 192 (1), 2. https://doi.org/10.1007/s10661-019-7959-1.

Ishizaka, A., Labib, A., 2011. Review of the main developments in the analytic hierarchy process. Expert Syst. Appl. 38 (11), 14336–14345. https://doi.org/10.1016/j.eswa.2011.04.143.

Jankowski, P., Ligmann-Zielinska, A., Swobodzinski, M., 2008. Choice modeler: a web-based spatial multiple criteria evaluation tool. T. GIS 12, 541–561. https://doi.org/10.1111/j.1467-9671.2008.01111.x.

Jenks, G.F. 1967. The Data Model Concept in Statistical Mapping. ⟨https://api.semanticscholar.org/CorpusID:215850874⟩.

Ki-Hyun Kim, E.K., Jahan, S.A., 2014. A review of the consequences of global climate change on human health. J. Environ. Sci. Health, Part C 32 (3), 299–318. https://doi.org/10.1080/10590501.2014.941279.

Lal, R., 2004. Carbon emission from farm operations. Environ. Int. 30, 981–990. https://doi.org/10.1016/j.envint.2004.03.005.

Lami, F., Boscutti, F., Peccol, E., Piani, L., De Luca, M., Zandigiacomo, P., Sigura, M., 2024. Biodiversity-centric habitat networks for green infrastructure planning: a case study in Northern Italy. Sustainability 16 (9). https://doi.org/10.3390/su16093604.

Li, Z., Fan, Z., Shen, S., 2018. Urban green space suitability evaluation based on the AHP-CV combined weight method: a case study of Fuping County, China. Sustainability 10 (8). https://doi.org/10.3390/su10082656.

Madureira, H., Andresen, T., 2014. Planning for multifunctional urban green infrastructures: promises and challenges. Urban Des. Int. 19. https://doi.org/10.1057/udi.2013.11.

Malczewski, J., 2006. GIS-based multicriteria decision analysis: a survey of the literature. Int. J. Geogr. Inf. Sci. 20 (7), 703–726. https://doi.org/10.1080/13658810600661508.

Malczewski, J., Rinner, C., 2015. Advances in Geographic Information Science Multicriteria Decision Analysis in Geographic Information Science⟨http://www.springer.com/series/7712⟩.

Mentzafou, A., Blagojević, M., Dimitriou, E., 2021. A GIS-MCDA-based suitability analysis for meeting targets 6.3 and 6.5 of the sustainable development goals. Sustainability 13 (8). https://doi.org/10.3390/su13084153.

Mészáros, C., Rapcsák, T., 1996. On sensitivity analysis for a class of decision systems. Decis. Support Syst. 16 (3), 231–240. https://doi.org/10.1016/0167-9236(95)00012-7.

Milošević, R., Šiljeg, S., Domazetović, F., 2023. GIS multicriteria decision analysis in selecting the optimal location for urban green space: a case study of Zadar City. Res. Publ. Connect 237–243. https://doi.org/10.5220/0012031400003473.

Mohamed Mouhoumed, R., Ekmekcioğlu, Ö., Özger, M., 2023. A hybrid MCDA approach for delineating sites suitable for artificial groundwater recharge using drywells. J. Hydrol. 620, 129387. https://doi.org/10.1016/j.jhydrol.2023.129387.

Mullan, D., Vandaele, K., Boardman, J., Meneely, J., Crossley, L.H., 2016. Modelling the effectiveness of grass buffer strips in managing muddy floods under a changing climate. Geomorphology 270, 102–120. https://doi.org/10.1016/j.geomorph.2016.07.012.

Nisyak, A.K., Ramdani, F., Suprapto, 2017. Web-GIS development and analysis of land suitability for rice plant using GIS-MCDA method in Batu city. Int. Symp. Geoinformat. 2017, 24–33. https://doi.org/10.1109/ISYG.2017.8280667.

Oliveira, S., Andrade, H., Vaz, T., 2011. The cooling effect of green spaces as a contribution to the mitigation of urban heat: a case study in Lisbon. Build. Environ. 46 (11), 2186–2194. https://doi.org/10.1016/j.buildenv.2011.04.034.

Osseni, A.A., Dossou-Yovo, H.O., Gbesso, F.G.H., Sinsin, B., 2023. GIS-based multi-criteria analysis for selecting suitable areas for urban green spaces in Abomey-Calavi District, Southern Benin. Land 12 (8). https://doi.org/10.3390/land12081553.

Ostberg, S., Lucht, W., Schaphoff, S., Gerten, D., 2013. Critical impacts of global warming on land ecosystems. Earth Syst. Dyn. 4 (2), 347–357. https://doi.org/10.5194/esd-4-347-2013.

Ozkiper, O., Allegri, E., Bianconi, A., Pham, H.V., Furlan, E., Simide, R., van der Geest, M., Critto, A., 2024. A GIS-MCDA approach to map environmental suitability of Posidonia oceanica meadows as blue nature-based solutions in the Mediterranean eco-region. Sci. Total Environ. 955, 176803. https://doi.org/10.1016/j.scitotenv.2024.176803.

Pan, H., Page, J., Shi, R., Cong, C., Cai, Z., Barthel, S., Thollander, P., Colding, J., Kalantari, Z., 2023. Contribution of prioritized urban nature-based solutions allocation to carbon neutrality. Nat. Clim. Change 13. https://doi.org/10.1038/s41558-023-01737-x.

Pant, K., 2009. Effects of agriculture on climate change: a cross country study of factors affecting carbon emissions. J. Agric. Environ. 10. https://doi.org/10.3126/aej.v10i0.2134.

Park, C.Y., Lee, D.K., Krayenhoff, E.S., Heo, H.K., Hyun, J.H., Oh, K., Park, T.Y., 2019. Variations in pedestrian mean radiant temperature based on the spacing and size of street trees. Sustain. Cities Soc. 48, 101521. https://doi.org/10.1016/j.scs.2019.101521.

Pelorosso, R., Leone, A., Boccia, L., 2009. Land cover and land use change in the Italian central Apennines: a comparison of assessment methods. Appl. Geogr. 29 (1), 35–48. https://doi.org/10.1016/j.apgeog.2008.07.003.

Pereira, P., Wang, F., Inacio, M., Kalinauskas, M., Bogdzevič, K., Bogunovic, I., Zhao, W., Barcelo, D., 2024. Nature-based solutions for carbon sequestration in urban environments. Curr. Opin. Environ. Sci. Health 37, 100536. https://doi.org/10.1016/j.coesh.2024.100536.

Proulx, F., Rodriguez, M., Sérodes, J., Bouchard, C., 2007. A methodology for identifying vulnerable locations to taste and odour problems in a drinking water system. Water Sci. Technol. A J. Int. Assoc. Water Pollut. Res. 55, 177–183. https://doi.org/10.2166/wst.2007.177.

Rahimi, A., 2016. A methodological approach to urban land-use change modeling using infill development pattern—a case study in Tabriz, Iran. Ecol. Process. 5 (1), 1. https://doi.org/10.1186/s13717-016-0044-6.

Ren, Y., Ge, Y., Ma, D., Song, X., Shi, Y., Pan, K., Qu, Z., Guo, P., Han, W., Chang, J., 2017. Enhancing plant diversity and mitigating BVOC emissions of urban green spaces through the introduction of ornamental tree species. Urban For. Urban Green. 27, 305–313. https://doi.org/10.1016/j.ufug.2017.08.011.

Ritchie, H. 2020. Sector by sector: where do global greenhouse gas emissions come from? Our World in Data.

Ricciardelli, I., Bacco, D., Rinaldi, M., Bonafè, G., Scotto, F., Trentini, A., Bertacci, G., Ugolini, P., Zigola, C., Rovere, F., Maccone, C., Pironi, P., Poluzzi, V., 2017. A three-year investigation of daily PM2.5 main chemical components in four sites: the routine measurement program of the Supersito Project (Po Valley, Italy). Atmospheric Environment 152, 418–430. https://doi.org/10.1016/j.atmosenv.2016.12.052.

Roy, D., Das, S., Paul, S., Paul, S., 2022. An assessment of suitable landfill site selection for municipal solid waste management by GIS-based MCDA technique in Siliguri municipal corporation planning area, West Bengal, India. Comput. Urban Sci. 2 (1), 18. https://doi.org/10.1007/s43762-022-00038-x.

Sachs, J., Kroll, C., Lafortune, G., Fuller, G., Woelm, F., 2022. Sustainable development report.

Sahana, M., Ravetz, J., Patel, P.P., Dadashpoor, H., Follmann, A., 2023. Where is the peri-urban? A systematic review of peri-urban research and approaches for its identification and demarcation worldwide. Remote Sens. 15 (5). https://doi.org/10.3390/rs15051316.

Salehin, Sk.M.-U.-, Ghimire, R., Angadi, S.V., Idowu, O.J., 2020. Grass buffer strips improve soil health and mitigate greenhouse gas emissions in center-pivot irrigated cropping systems. Sustainability 12 (15). https://doi.org/10.3390/su12156014.

San-Miguel-Ayanz, J., de Rigo, D., Caudullo, G., Durrant, T., Mauri, A., Tinner, W., Ballian, D., Beck, P., Birks, H., Eaton, E., Enescu, C., Salvatore, P., Popescu, I., Ravazzi, C., Welk, E., Abad Viñas, R., Azevedo, J., Barbati, A., Barredo, J., Zecchin, B., 2016. Eur. Atlas For. Tree Species.

Shalaby, A., Tateishi, R., 2007. Remote sensing and GIS for mapping and monitoring land cover and land-use changes in the Northwestern coastal zone of Egypt. Appl. Geogr. 27 (1), 28–41. https://doi.org/10.1016/j.apgeog.2006.09.004.

Shorabeh, S.N., Firozjaei, M.K., Nematollahi, O., Firozjaei, H.K., Jelokhani-Niaraki, M., 2019. A risk-based multi-criteria spatial decision analysis for solar power plant site selection in different climates: a case study in Iran. Renew. Energy 143, 958–973. https://doi.org/10.1016/j.renene.2019.05.063.

Short Gianotti, A.G., Getson, J.M., Hutyra, L.R., Kittredge, D.B., 2016. Defining urban, suburban, and rural: a method to link perceptual definitions with geospatial measures of urbanization in central and eastern Massachusetts. Urban Ecosyst. 19 (2), 823–833. https://doi.org/10.1007/s11252-016-0535-3.

Shu, Y., Lam, N., Reams, M., 2010. A new method for estimating carbon dioxide emissions from transportation at fine spatial scales. Environ. Res. Lett. 5, 44008. https://doi.org/10.1088/1748-9326/5/4/044008.

Shukla, P.R., Skea, J., Slade, R., Fradera, R., Pathak, M., Belkacemi, M., Hasija, A., 2022. IPCC, Climate Change 2022: Mitigation of Climate Change.

Sowińska-Świerkosz, B., García, J., 2022. What are Nature-based solutions (NBS)? Setting core ideas for concept clarification. Nat. Based Solut. 2, 100009. https://doi.org/10.1016/j.nbsj.2022.100009.

Stemmer, B., Kaußen, L., Bernstein, F., 2021. Gis-landscape quality assessment using social media data. J. Digit. Landsc. Archit. 2021 (6), 295–305. https://doi.org/10.14627/537705026.

Stocker, T.F., Qin, D., Plattner, G.K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V., Midgley, P.M., 2013. IPCCIPCC, Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.

Sun, J., Wang, Y., Lee, T.M., Nie, X., Wang, T., Liang, E., Wang, Y., Zhang, L., Wang, J., Piao, S., Chen, F., Fu, B., 2024. Nature-based Solutions can help restore degraded grasslands and increase carbon sequestration in the Tibetan Plateau. Commun. Earth Environ. 5 (1), 154. https://doi.org/10.1038/s43247-024-01330-w.

Sutton, Paul C., Goetz, Andrew R., S, F., C.F., Ghosh, T., 2010. Darkness on the edge of town: mapping urban and peri-urban Australia using nighttime satellite imagery. Prof. Geogr. 62 (1), 119–133. https://doi.org/10.1080/00330120903405006.

Tassinari, P., Torreggiani, D., 2006. Location planning: a methodological approach for agro-industrial buildings in rural territory. Trans. ASABE 49, 505–516. https://doi.org/10.13031/2013.20405.

Threlfall, C.G., Mata, L., Mackie, J.A., Hahs, A.K., Stork, N.E., Williams, N.S.G., Livesley, S.J., 2017. Increasing biodiversity in urban green spaces through simple vegetation interventions. J. Appl. Ecol. 54 (6), 1874–1883. https://doi.org/10.1111/1365-2664.12876.

Tong, D., Zhang, Q., Zheng, Y., Caldeira, K., Shearer, C., Hong, C., Qin, Y., Davis, S., 2019. Committed emissions from existing energy infrastructure jeopardize 1.5 °C climate target. Nature 572, 1. https://doi.org/10.1038/s41586-019-1364-3.

Udawatta, R.P., Jose, S., 2012. Agroforestry strategies to sequester carbon in temperate North America. Agrofor. Syst. 86 (2), 225–242. https://doi.org/10.1007/s10457-012-9561-1.

Ustaoglu, E., 2022. An assessment of land use/cover suitable for peri-urban green space development: an example of an integration of gis with the multi-criteria analysis (MCA) approach. Eur. Sci. J., ESJ 18 (35), 1. https://doi.org/10.19044/esj.2022.v18n35p1.

Verlinden, M.S., Broeckx, L.S., Zona, D., Berhongaray, G., De Groote, T., Camino Serrano, M., Janssens, I.A., Ceulemans, R., 2013. Net ecosystem production and carbon balance of an SRC poplar plantation during its first rotation. Biomass Bioenergy 56, 412–422. https://doi.org/10.1016/j.biombioe.2013.05.033.

Vidal, D., Barros, N., Maia, R., 2020. Public Green. Spaces Context Sustain. Dev. 479–487. https://doi.org/10.1007/978-3-319-95717-3_79.

Vizzari, M., 2011. Spatial modelling of potential landscape quality. Appl. Geogr. 31 (1), 108–118. https://doi.org/10.1016/j.apgeog.2010.03.001.

Wang, F., Liu, J., Qin, G., Zhang, J., Zhou, J., Wu, J., Zhang, L., Thapa, P., Sanders, C.J., Santos, I.R., Li, X., Lin, G., Weng, Q., Tang, J., Jiao, N., Ren, H., 2023. Coastal blue carbon in China as a nature-based solution toward carbon neutrality. Innovation 4 (5). https://doi.org/10.1016/j.xinn.2023.100481.

Watson, J.J.W., Hudson, M.D., 2015. Regional Scale wind farm and solar farm suitability assessment using GIS-assisted multi-criteria evaluation. Landsc. Urban Plan. 138, 20–31. https://doi.org/10.1016/j.landurbplan.2015.02.001.

Xi, C., Ding, J., Wang, J., Feng, Z., Cao, S.-J., 2022. Nature-based solution of greenery configuration design by comprehensive benefit evaluation of microclimate environment and carbon sequestration. Energy Build. 270. https://doi.org/10.1016/j.enbuild.2022.112264.

Xie, X., Kang, H., Behnisch, M., Baildon, M., Krüger, T., 2020. To What Extent Can the Green Belts Prevent Urban Sprawl?—A Comparative Study of Frankfurt Am Main, London and Seoul. Sustainability 12 (2). https://doi.org/10.3390/su12020679.

Xie, H., Yao, G., Liu, G., 2015. Spatial evaluation of the ecological importance based on GIS for environmental management: A case study in Xingguo county of China. Ecol. Indic. 51, 3–12. https://doi.org/10.1016/j.ecolind.2014.08.042.

Yasuhara, K., Murakami, S., Mimura, N., Komine, H., Recio, J., 2007. Influence of global warming on coastal infrastructural instability. Sustain. Sci. 2 (1), 13–25. https://doi.org/10.1007/s11625-006-0015-4.

Yoro, K.O., Daramola, M.O., 2020. Chapter 1 - CO2 emission sources, greenhouse gases, and the global warming effect. In M. R. Rahimpour. In: Farsi, M., Makarem, M.A. (Eds.), Advances in Carbon Capture. Woodhead Publishing, pp. 3–28. https://doi.org/10.1016/B978-0-12-819657-1.00001-3.

Zaniboni, A., Tassinari, P., Torreggiani, D., 2024. GIS-based land suitability analysis for the optimal location of integrated multi-trophic aquaponic systems. Sci. Total Environ. 913, 169790. https://doi.org/10.1016/j.scitotenv.2023.169790.

Zhang, X., Huang, H., Tu, K., Li, R., Zhang, X., Wang, P., Li, Y., Yang, Q., Acerman, A., Guo, N., Liu, Y., 2024. Effects of plant community structural characteristics on carbon sequestration in urban green spaces. Sci. Rep. 14. https://doi.org/10.1038/s41598-024-57789-2.

Zoras, S., Triantafyllou, A.G., Hurley, P.J., 2007. Grid sensitivity analysis for the calibration of a prognostic meteorological model in complex terrain by a screening experiment. Environ. Model. Softw. 22 (1), 33–39. https://doi.org/10.1016/j.envsoft.2005.09.010.

Zucca, A., Sharifi, M., Fabbri, A., 2008. Application of spatial multi-criteria analysis to site selection for a local park: a case study in the Bergamo Province, Italy. J. Environ. Manag. 88, 752–769. https://doi.org/10.1016/j.jenvman.2007.04.026.

Web references

Archivio Cartografico, Geoportale Regione Emilia-Romagna, 2024. Archive of historical and contemporary cartographic resources of Emilia-Romagna. https://geoportale.regione.emilia-romagna.it/ (accessed 2 September 2024).

Comune di Bologna, 2024. Official website of the municipality of Bologna. https://www.comune.bologna.it/ (accessed 2 September 2024).

Copernicus – Europe's eyes on Earth; Programme of the European Union (2018). CORINE Land Cover website provides European land cover and land use data. It supports environmental monitoring, spatial planning, and policy-making across Europe with detailed datasets for various land types and changes over time. https://land.copernicus.eu/en/products/corine-land-cover (accessed 2 September 2024).

Earth Explorer, USGS, 2024. Platform providing access to satellite, aerial imagery and geospatial data https://earthexplorer.usgs.gov/ (accessed 2 September 2024).

Earthdata Search, NASA, 2024. Search interface for accessing NASA's Earth observation data and resources. https://search.earthdata.nasa.gov/ (accessed 2 September 2024).

Geoportale Regione Emilia-Romagna, 2024. Regional geographic information system portal of Emilia-Romagna. https://geoportale.regione.emilia-romagna.it/ (accessed 2 September 2024).

GID Model, 2024. Website offering access to global geospatial data quantifying greenhouse gas and air pollutant emissions. http://www.gidmodel.org.cn/ (accessed 2 September 2024).

Istituto Nazionale di Statistica (ISTAT), 2024. Italian National Institute of Statistics website http://www.istat.it/ (accessed 2 September 2024).

Livestock Data, 2024. Platform providing global livestock statistics and data resources. http://www.livestockdata.org/ (accessed 2 September 2024).

Overpass Turbo, 2024. Web-based tool for querying and visualizing OpenStreetMap data. http://www.overpass-turbo.eu/ (accessed 27 September 2024).