Land Suitability Analysis of Nature-Based Solutions for Climate Adaptation and Mitigation in the Sardinia Region, Italy

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Abstract. The study investigates the improvement of urban ecological infrastructure via urban and peri-urban forestation initiatives. The study focuses on Blue and Green Infrastructure (BGI) in vulnerable urban areas as a relevant solution to fostering sustainable development and addressing climate change adaptation and mitigation. By integrating multi-criteria spatial analysis and statistical models, the study develops a replicable procedure to identify suitable areas for BGI interventions, ensuring optimised use of financial resources and maximising environmental, social, and economic benefits. The procedure is aimed at organising the information required for implementing the Geodesign process in the context of defining strategies for adaptation to and mitigation of climate alteration. It is applied to a case study in Sardinia, Italy. The study's findings demonstrate the relevance of the procedure to the spatialisation of public policies, enabling evidence-based decisions in the context of integrating mitigation and adaptation strategies into urban regeneration and sustainable development plans.

Keywords: Climate Change · Mitigation · Adaptation · Nature Based Solutions · Urban Forests · Sardinia

1 Introduction

The sustainable development of urban areas is a critical step for contributing to goals defined at global, regional, national, sub-national and local levels [1]. The trends of urbanisation and the persistence of unsustainable forms of production and consumption are responsible for the increasing role of cities as major drivers of climate alteration and as areas vulnerable to climate change impacts. Consequently, implementing transformative strategies for sustainable and resilient cities is central to enable integrated sustainable development and mitigation of and adaptation to climate alterations. The proposed study

This paper is the result of the joint work of the authors. 'Abstract', 'Methodology', 'Results' and 'Conclusions' were written jointly by all authors. Francesco Scorza wrote the 'Introduction', Chiara Garau wrote the 'Discussion' and Alfonso Annunziata the 'Literature review'.

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O. Gervasi et al. (Eds.): ICCSA 2025 Workshops, LNCS 15896, pp. 16–33, 2026.
https://doi.org/10.1007/978-3-031-97654-4_2

is part of a research on "Geodesign for climate change mitigation and adaptation in the Mediterranean region". Geodesign utilises a comprehensive methodology to investigate inter-systemic interactions across distinct spatial and temporal scales [2] and develops a structured and iterative process for enabling informed decisions [3–5]. As a result, Geodesign represents a valid tool to respond to issues determined by climate alteration [5, 6]. The proposed study focuses on urban ecological infrastructures and emphasises interventions of urban and peri-urban forestation. Expanding the urban ecological infrastructure is a strategy based on the nature-based solutions perspective. Interventions of urban and peri-urban forestation are relevant to provide environmental, social, and economic benefits, including improved climate resilience and climate regulation, carbon sequestration and storage, conservation of urban biodiversity and regeneration of public spaces for recreation and social activities. This research examines the identification of areas most suitable to interventions of Blue and Green Infrastructures (BGI) reinforcement. The objective is to contribute in the optimisation of limited financial resources and maximise the related environmental, social and economic benefits. This study adopted multi-criteria spatial analysis and statistical models to develop a replicable procedure aimed at: i) identifying vulnerable parts of urbanised areas most suitable to BGI development; ii) identifying clusters of urbanised land units presenting similar suitability levels. The proposed procedure is tested in the case study of the Sardinia Region, in Italy. The relevance of the study results from distinct aspects: i) defining the optimal location for interventions relevant to climate alteration adaptation and mitigation; ii) underlining the relevance of the spatial dimension in the definition of mitigation and adaptation strategies. As a result, the study contributes to enabling evidence-based decisions in the context of urban adaptation plan development and integrating mitigation/ adaptation criteria into urban regeneration and sustainable development plans. The article is organised into six sections: after the introduction, a review of the scientific literature is presented in Sect. 2. The methodology section describes data, tools, models and indicators utilised to implement the procedure. Section 4 presents the findings related to the identification of clusters of urbanised land units and the computation of a metric of site suitability. Section 5 discusses the findings from the analysis. Finally, the Conclusions delineate the significance of the study's results, the limits of the methodology, and the pertinent directions for the study's advancement. The study contributes to studies on the alignment of sustainable development and adaptation/ mitigation initiatives and the development of decision support model for the spatialization of mitigation and adaptation policies [7, 8].

2 Literature Review

2.1 Climate Alterations and Cities

Sustainable development is defined as a form of development that seeks to satisfy the requirements of both present and future generations. The United Nations 2030 Agenda for sustainable development outlines an ambitious vision on development articulated in a set of transformative goals and targets [9]. Contrasting climate alteration is recognised as a requirement for sustainable development. The Sustainable Development Goal (SDG) 11 also indicates the construction of safe, resilient and sustainable cities as a condition

for sustainable development [9, 10]. The role of urban sustainable development as a driver of global sustainable development is reiterated by the New Urban Agenda [1, 11] and, at a regional level, by the Urban Agenda for The European Union [12] and the New Leipzig Charter [13]. Moreover, cities and urbanisation trends determine interdependent consequences relevant to climate alteration: emergence of urbanised areas as major sources of GHG (Greenhouse gasses) emissions [14, 15]; and increased vulnerability and exposure of urbanised areas to climate alteration impacts. The proportion of urban emissions on global emissions is significant and continues to increase [15, 16], from 25 $GtCO_2eq$ in 2015, equal to 62% of global emissions, to 29 $GtCO_2eq$ in 2020 equal to 62–72% of global emissions. Urban emissions are also influenced by urban structural factors, including urban form, density and size [17]. Consequently, trends in urban land use and urban form transformation influence future urban environmental impact and long-term mitigation potential. Moreover, interactions among modification in urban form, exposure and vulnerability and direct climate impacts can engender potential adverse impacts specific to individual urban areas [17]. For instance, temperature increase due to climate alterations can amplify the multi-scale adverse impacts of the urban heat island (UHI) [18, 19]. UHI refers to localised elevated temperature in the urban environment, determined by the material properties and spatial configuration of the built environment and heat release from urban functions [17]. Cities' levels of exposure to river, pluvial, sewer and coastal floods [17] are increased as a result of continued increase in global surface temperatures and urban structure modification resulting in land use conversion and soil sealing [20, 21]. Consequently, adaptation and mitigation measures in urban areas become central to mitigating climate change and enhancing resilience, as well as to urban sustainable development strategies. The 2030 Agenda [9], the New Urban Agenda [1], and the Urban Agenda for the EU [12, 13] advocate for the implementation of integrated policies aimed at enhancing resilience to catastrophes, as well as adapting to and mitigating climate change, as fundamental criteria for urban sustainable development. Specifically, combining mitigation actions and integrating Sustainable Development Goals can catalyse sustainable urban developmental trajectories. At the same time, interferences among mitigation options, and among mitigation, adaptation and sustainable development goals are to be considered [15]. For instance, a need emerge for defining optimal level of density so as to avoid fragmentation and reduction of blue and green infrastructure and consequent UHI intensification [22–24].

2.2 Adaptation and Mitigation Actions for Urban Areas

Key strategies for coupling mitigation, adaptation, and sustainable development benefits encompass land use diversity and density, intrinsic to the Transit Oriented Development, 15-minute city and Neighbourhood Unit models [25], electrification and decarbonisation of urban energy systems, improving buildings energy performance, transition to net-zero emissions materials in the construction sector [26, 27], increased mobility options, prioritising active travel and public transit, avoiding, minimising and recycling waste [28] and blue and green infrastructure [29]. Urban BGIs refer to a strategic perspective aimed at developing continuous and multi-functional structures of green and blue spaces [30]. Urban BGI is a form of Nature-based Solutions (NBS). NBS are solutions based on

nature and use the metabolism of ecosystems as infrastructure to provide natural services [31], increasing climate resilience, generating co-benefits for society, and ensuring the protection, sustainable management and restoration of natural or modified ecosystems [32].Urban BGIs include a broad set of natural and semi-natural spaces including forests, agricultural land, urban green areas, private gardens, ponds, streams and single green elements (green roofs, green façades, street trees) [15, 30]. Urban BGIs produce benefits in terms of mitigation, adaptation and SDGs realisation [29, 33, 34]. In particular, urban forests provide reduced building energy use, reduced water use, conditions conducive to active travel, and carbon storage and sequestration [15]. Adaptation co-benefits include reduced local temperatures, reduced incidence of cardiovascular and respiratory diseases, flooding mitigation, improved air quality and biodiversity protection [35, 36]. Mitigation benefits, in terms of carbon sequestration, are estimated to be an average of 2.05 tCha-1y-1 in functional urban areas in the United States [37] and 2.67 tCha-1y-1 in a case study conducted in Madrid, Spain [38]. Teo et al. [39] estimate a global carbon sequestration potential of 82.4 $(+ - 25.7)$ $MtCO_2ey^{-1}$. In terms of micro-climate regulation a tree cover of 16% of urbanised areas can result in a temperature decrease of 1 °C [35]. Lastly, urban forests are relevant to Sustainable Development goals and targets relative to the development of safe, resilient and sustainable cities: urban forest contribute, in fact, to developing a continuous infrastructure of open, inclusive, multipurpose, usable safe open spaces, for promoting vibrant urban environment, improving air quality, quality of life and increasing resilience [1, 13]. The study presented in the subsequent sections outlines a procedure for evaluating the suitability of urban areas for forestation interventions at the census tract level, considering climatic, structural, and land use factors.

3 Methodology

The procedure combines spatial multicriteria analysis and statistical analysis to evaluate the suitability of urban areas in the Sardinia Region, to intervention of BGI development and, in particular, of urban forestation relevant to adapting to and mitigating climate alteration. The procedure is organised in six stages (Fig. 1): i) selection of relevant spatial units; ii) selection of relevant criteria and sub-criteria; iii) selection of pertinent indicators, indicators computation and normalisation; iv) computation of the load-factors for the sub-criteria and for the criteria, based on distinct scenarios; v) computation of a composite indicator for the selected criteria and of a composite indicator of land suitability (ISUF) for the proposed scenarios; vi) analysis of the spatial auto-correlation for the indicators related to the selected criteria and for the composite indicator of land suitability determined under the proposed scenarios.

3.1 Selection of Spatial Units

The census tracts from the 2021 National Census representing urbanised areas in the Sardinia Region (Fig. 2) are selected as the units of analysis [40]. Census tracts are selected based on the value of the categorial variable ‘location type’. More precisely, census tracts labelled as urban centers, or urbanised clusters are selected as units of

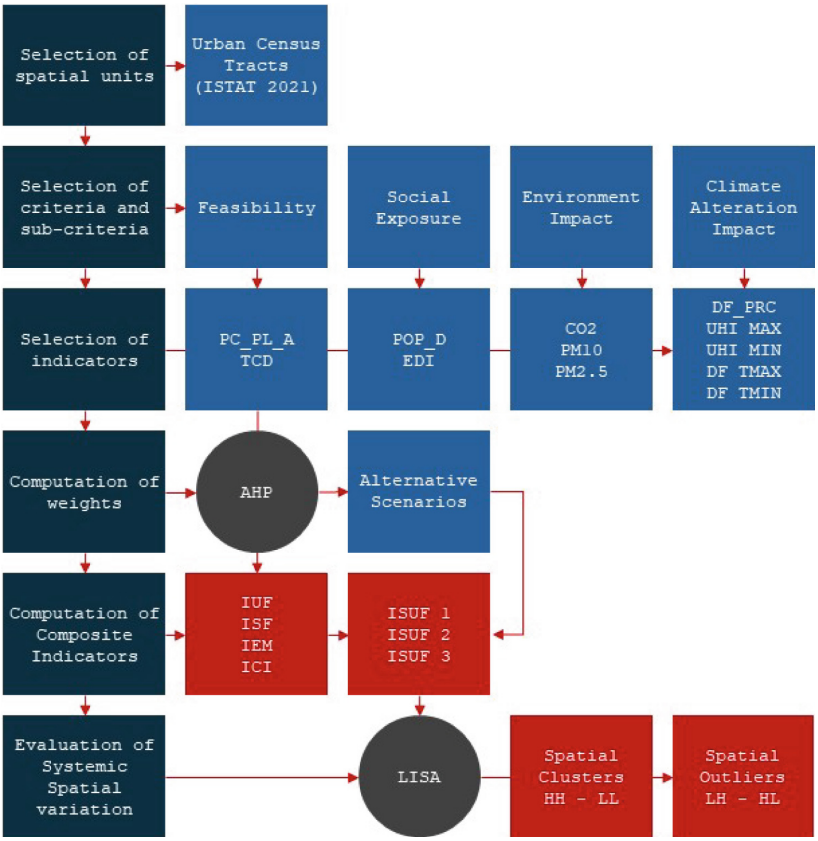

Fig. 1. Organization of the proposed procedure.

analysis. Selecting census tracts as units of analysis is instrumental to obtaining a granular representation of the spatial variability of conditions of suitability to specific mitigation and adaptation actions across an urban area.

3.2 Criteria and Sub-criteria Selection

The selection of criteria and sub-criteria is representative of the need to optimise the localisation of interventions for maximising benefits in terms of adaptation to and mitigation of climate alteration. The criteria refer to four dimensions: i) feasibility of the action; ii) social exposure; iii) Environmental impact of urbanised areas; iv) magnitude of climate alteration impacts.

The feasibility of the intervention is related to urban form factors, which represent the sub-criteria. These include the presence of plantable areas, and the tree cover density. The second criterion refers to the exposure of the population to climate alteration impacts mitigated by urban forests. The sub-criteria are population density and percentage of vulnerable individuals. Urbanised areas' environmental impact includes the sub-criteria

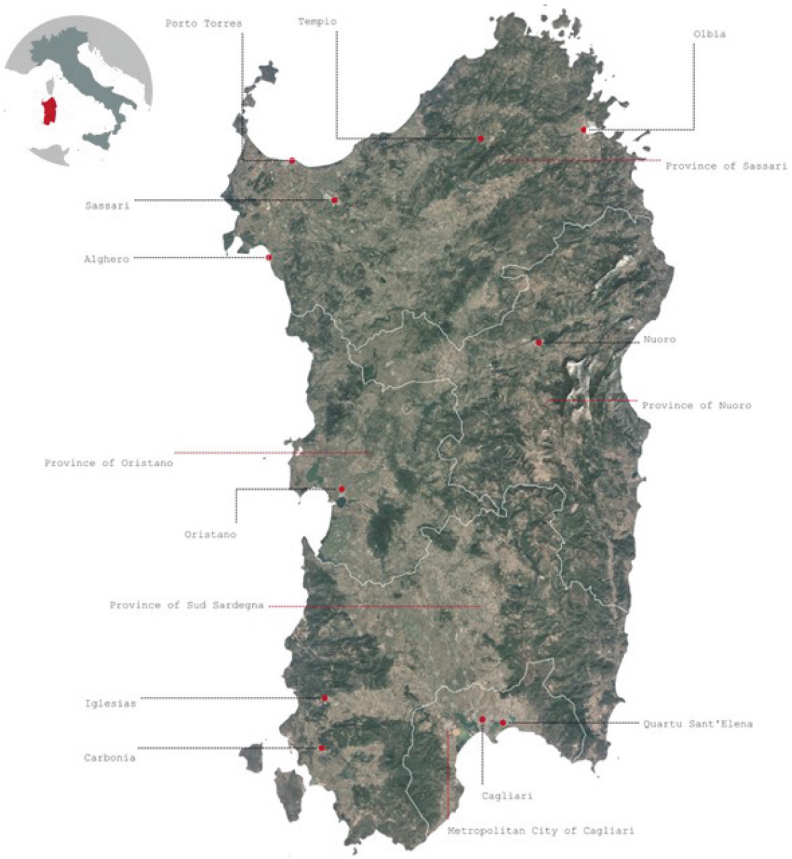

Fig. 2. Selection of the Area of Study.

intensity of CO_2 emissions, PM 10 concentration and PM 2.5 concentration. Lastly, the magnitude of climate alteration impacts includes the sub-criteria Variation of precipitation patterns, diurnal and nocturnal Urban Heat Island and variation of minimum and maximum temperatures. Localised elevated temperature, temperature increase, and precipitation variation represent, in fact, climate alteration impacts mitigated by urban forestation interventions.

3.3 Selection, Computation and Normalisation of the Indicators

The procedure is based on 12 indicators representing the selected sub-criteria. The presence of plantable areas is operationalised in terms of the ratio of permeable land, presenting a tree cover density minor than 50%, on the surface area of the i-th census tract. Information on land cover is derived from the CLCplus Backbone 2021 layer. The latter provides a detailed land cover inventory for the 2021 reference year, in the spatial resolution of 10 m, representing for each cell the dominant land cover among the 11 basic land cover classes [41]. Tree Cover Density is measured in terms of the average value,

for each census tract, of tree cover density derived from the Layer Tree Cover Density (TCD) retrieved from the Copernicus Land Monitoring Service (CLMS). The TCD layer provides the level of tree cover density in a range from 0% to100% at pan-European level in the spatial resolution of 10 m for the 2018 reference year [42].

Population density is computed as the number of individuals per ha residing in the i-th census tract. Data related to resident population per census tract and census tract surface area are retrieved from the dataset Territorial Bases and Census Variables for the reference year 2021 of the Italian National Statistic Institute (ISTAT) [40]. The percentage of vulnerable individuals refers to the proportion of the elderly population for each census tract and it is operationalised in terms of the elderly dependency index. Elderly population is, in fact, vulnerable to temperature increase and localised elevated temperatures in urban areas, resulting from and amplified by climate alteration [15]. The Elderly Dependency Index is computed for each census tract as the ratio of the population of age superior to 65 years on the population of age comprised in the 15–64 years range. The CO_2 emissions intensity is computed as the mean value, for each census tract, of the value averaged over 12 months of cumulated CO_2 emissions. The indicator is based on the Anthropogenic emissions of CO_2 Layer retrieved from the global emission inventories of the Copernicus Atmosphere Monitoring Service [43]. The dataset provides the cumulated emission intensity from 12 sectors, measured in $KgCO_2\ m^{-2}\ s^{-1}$, for the 2019 reference year, at a spatial resolution of 0.1°. The values are converted in $tCO_2\ Km^{-2}\ year^{-1}$ and the raster layer is reprojected, resampled via a B-spline interpolation at a spatial resolution of 1 km and clipped to the area of interest. Similarly, PM10 and PM2.5 concentration levels are computed as the mean value for individual census tracts, of the annual average of concentration levels of PM10 and PM2.5, measured in micrograms per cubic meter of air ($\mu g/m^3$). Data are derived from the pm10, European air quality data for 2022, and from the pm2.5, European air quality data for 2022 [44]. The data set provides concentrations levels for PM2.5 and PM10 at a spatial resolution of 1 km. The raster layers are reprojected, resampled via a B-spline interpolation at a spatial resolution of 500 m and clipped to the area of interest. Average CO2 emission intensity and PM10 and PM2.5 concentration levels at census tracts level are computed via the zonal statistic function in a GIS environment, by averaging the related values of the cells comprised in the census tract. Precipitation regime alteration is computed, for the i-th census tract, as the variation among the average of annual precipitations in the 1970–2000 period and the average of estimated annual precipitations in the 2021–2040 period. Urban Heat Island during day and night hours are computed at census tract level respectively as the variation in maximum and minimum temperature averaged over the summer season among the i-th census tract and contiguous rural areas. Contiguous rural areas are defined via a multi-step procedure based on Wang et al. [45, 46]. The procedure includes creation of 12 buffers of the urban clusters at varying radii; selection of the area delimited by the boundaries of the 12th and ninth buffer; removal of areas covered by water; selection of areas with elevation ranging from −50 m to +50 m from the mean elevation of the relevant urban cluster. The radius of the i-th buffer is determined so that the area delimited by the boundaries of the i-th buffer and the i-th – 1 buffer is half the surface area of the related urban cluster. Minimum and Maximum temperature variation are computed, respectively, as the divergence among the mean

summer maximum temperature and the summer minimum temperature averaged over the 1970–2000 period and the estimated mean summer maximum temperature and summer minimum temperature averaged over the 2021–2040 period. Subsequently, the maximum and minimum temperature variations for each census tract are calculated by averaging the corresponding values of the cells contained in the census tract. Precipitation data and Temperature data are derived from the Historical Climate Data and the Future Climate Data datasets of the WorldClim data service [47, 48]. Data are provided as raster grids at a spatial resolution of 1 Km. The raster layers are reprojected, resampled via a B-spline interpolation at a spatial resolution of 200 m and clipped to the area of interest. Data related to the 2021–2040 period derive from estimates computed under the Shared Socio-economic Pathway (SSP) 370, for the Global Climate Model (GCM) GISS-E2–1-G. SSP 370 refers to a scenario of moderate implementation of mitigation and adaptation actions in a context of resurgent nationalism, concerns about competitiveness and security, and regional conflicts [49, 50].

3.4 Weighting of Sub-criteria and Criteria

The weights of the criteria and the sub-criteria are determined via the Analytical Hierarchy Process (AHP), developed by Thomas Saaty in the 1970s [51]. It is a measurement procedure based on a process of problems' decomposition via the identification of an objective and the determination of the criteria, sub-criteria and alternatives relevant to realising the objective. AHP reduces the complexity of a problem via a pairwise comparison technique integrated into a multi-level structure: the multi-level structure is used to represent the problem and pairwise comparisons are used to determine relations among the variables comprised in a same level [51, 52]. In the discrete case the comparisons result in dominance matrices and in the continuous case in kernels of Fredholm operators. Comparisons are formalised in terms of a dominance factor $\boldsymbol{c_{ij}}$ representing the relative importance of element i compared to element j of the same level in relation to element k of the superior level. The dominance matrices are positive and reciprocal, e.g. $\mathbf{c_{ij}} = 1/\mathbf{c_{ji}}$. A qualitative evaluation, based on a semantic scale, can be provided if the dominance factor cannot be determined quantitatively. The value scale proposed by Saaty [53] enables the conversion of qualitative and comparative evaluations into quantitative terms. The matrix is an n*n structure, where n is the number of elements being compared. The value in row i and column j of the matrix indicates the relative importance of element i over element j concerning a variable k of the superior level. The comparison matrices are normalised by dividing each dominance factor c_{ij} by the sum of the values in the same column. The average of the values in row i of the normalised matrix represents the weight of the i-th element. The level of evaluations' consistency is determined by calculating the Consistency Ratio (CR). If CR is superior to 0.1 a re-examination of the judgements in the comparison matrix is often required. CR is given by the ratio between the Consistency Index (CI) and the Random Consistency Index (RCI). CI is obtained via Eq. 1:

$$CI = \frac{\lambda_{max} - n}{n - 1} \tag{1}$$

λ_{max} represents the principal eigenvalue of the comparison matrix. Lastly, the Random Consistency Index, is a predetermined value, and is a function of the number n of elements considered.

3.5 Computation of a Composite Indicator of Site Suitability

The computation of criteria's priorities considers the definition of distinct scenarios. In scenario 1 the Magnitude of Climate Alteration impacts is considered more important, and the feasibility of the action is considered of minor significance. In scenario 2 the feasibility of the action and the magnitude of climate alteration impacts are evaluated as more significant and impact on climate alteration is considered as the least important criterion. Lastly, in scenario 3, Social Exposure is prioritised over the remaining criteria. Concerning sub-criteria, the percentage of plantable areas and Tree Cover density are considered of equal importance in relation to the feasibility of the actions. Similarly, Population density and the Elderly Dependency Index are given equal priority concerning the level of social exposure to climate alteration impacts. Regarding urbanised areas' environmental impact, the concentration of PM10 and PM2.5 are considered of equal significance and more important compared to Intensity of CO_2 emissions. Benefits provided by urban forests in terms of reduction of particulate concentration and improved air quality [54] are considered more relevant to local urban populations compared to forests' contribution to mitigation via carbon sequestration, given the supralocal dimension of climate alteration. Regarding the magnitude of climate alteration impacts, the increase in minimum and maximum temperatures is considered more relevant compared to UHI and alteration in precipitation regimes. For each criterion, an index is calculated as the sum of the products of the pertinent sub-criteria metrics and their respective weights. The resulting indicators represent the suitability of the spatial units in relation to individual criteria: IUF formalises the feasibility of the intervention, ISF social exposure, IEM formalises urban environmental impacts and ICI measures the magnitude of relevant climate alteration impacts. Lastly, a composite indicator of land suitability (ISUF) is computed as the sum of the products of the criteria indexes and the respective weights determined for each alternative scenario.

3.6 Spatial Autocorrelation

A local Indicator of Spatial Association [55] is computed to evaluate the presence of systematic spatial variation in the Indicator of Land Suitability. Spatial autocorrelation statistics are designed to reject the null condition of spatial randomness in favour of an alternative of clustering. The selected Indicator is the Local Moran's I, computed via the GeoDa software tool, version 1.22 [56]. The Local Moran's I is computed, for a location i, as the product of the value of a variable and its spatial lag (see Eq. 2).

$$I = \frac{z_i * \sum_j w_{ij} * z_j}{\sum_i z_i^2} \tag{2}$$

The spatial lag of a variable measured at location i is formalised as the sum of the values measured at adjacent locations multiplied by a factor determined by a function of the

distance of the adjacent locations from location i. If adjacent observations present similar data values the map indicates positive spatial autocorrelation. If adjacent observations tend to present contrasting values, then a negative spatial autocorrelation is observed. The direction of the relation is visualised via a plot, denominated a Moran scatterplot, that presents the spatial lag of the variable on the y-axis and the original variable on the x-axis. Significance is measured via a pseudo p-value derived from a conditional permutation procedure. As a result, given a location i, the values of the n-1 remaining observations are randomly permuted to generate a reference distribution. Subsequently, the p-value is computed as a function of the number of permutation (M) and the number of times the Local statistics computed from the random data sets is equal or superior to the observed statistic (R) (Eq. 3).

$$p = \frac{R + 1}{M + 1} \tag{3}$$

The evaluation of significance and of the location of individual observations in the Moran Scatterplot results in the identification of four types of clustering: observations presenting values above the mean, and adjacent to observations presenting similar values form a High-High (HH) cluster. Observations presenting values below the mean and adjacent to observations presenting values below the mean form a Low-Low (LL) cluster. High-Low (HL) and Low-High (LH) outliers refer respectively to observations presenting values above the mean adjacent to observations presenting contrasting values and observations presenting values below the mean adjacent to observations presenting values above the mean. An exploratory statistical analysis using the Average Comparison Chart is conducted to characterise the suitable areas under the alternative scenarios, enabling the identification of statistically significant differences in the mean values of selected sub-criteria between suitable and non-suitable census tracts.

4 Results

The computation of the composite indicator of land suitability under alternative scenarios indicate a general moderate condition of suitability of urban census tracts to interventions of urban forestation. More precisely, the indicator computed under scenario 1 indicates levels of suitability ranging from 0.197 to 0.582, a mean value of 0.374 and a median of 0.376. Under scenario 2, levels of suitability range from 0.181 to 0.646. The mean value is 0.432 and the median is equal to 0.430. Lastly, the composite indicator computed under scenario 3 presents values comprised in the interval 0.128–0.597, a mean value of 0.305 and a median of 0.303 (Fig. 3).

The Local Moran's I underlines significant spatial relations for scenario 1, indicated by a value of the statistic of 0.803, a moderate level of interdependence for scenario 2, indicated by a value of Local Moran's I of 0.476, and a modest spatial relation under scenario 3, indicated by a Local Moran's I equal to 0.330. Focusing on Scenario 1 (Fig. 2), a significant p-value (<0.005), derived from 999 permutations, is observed for 36.1% of urban census tracts, and adequate levels of significance, indicated by a p-value inferior to 0.05 is observed for 7730 census tracts, equal to 56.6% of the selected sample. The evaluation of the direction of the correlation indicates that 3822 census

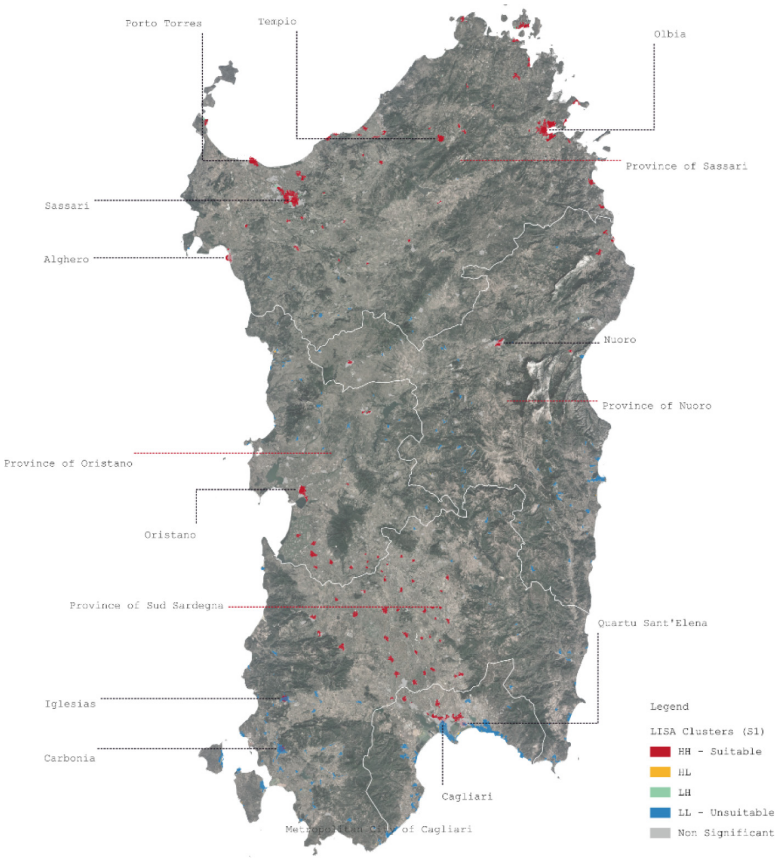

Fig. 3. Clusters Derived from Local Moran's I, under scenario 1. Census Tracts categorised as High-High Clusters are identified as Suitable Locations.

tracts, equal to 27.9% of the sample, present levels of suitability above the mean and positively related to levels of suitability observed at adjacent locations. As a result, 3822 census tracts are comprised in HH clusters. Vice versa, 3312 census tracts, equal to 24.2% of the sample, are comprised in LL clusters. Observations in LL clusters present levels of suitability below the mean and positively related to values computed at adjacent locations. A limited percentage of census tracts, equal respectively to 0.06% and 0.07% is categorised as spatial outliers, comprised in LH and HL clusters: 83 census tracts present values below the mean negatively related to values observed at adjacent locations (LH clusters) and 101 census tracts present values above the mean and are contiguous to locations presenting values below the mean (HL clusters). HH clusters are located in semi-central and periurban areas of main urbanised regions, including Cagliari, Oristano, Sassari and Olbia and in urban clusters in the Campidano Plain. LL clusters include urban centres in the Sulcis Iglesiente province and in mountainous internal areas in the Nuoro Province, and central compact districts and costal urbanised areas in the Metropolitan City of Cagliari (MCC). As a result, Considering plantable

areas located in urban census tracts presenting values of the composite indicator of land suitability above the mean and adjacent to location presenting analogous values, a total surface area of 3490.11 ha is suitable to interventions of urban forestation, under scenario 1.Under Scenario 2, derived from prioritising criteria of feasibility and magnitude of climate alteration impact, 3218,28 ha of plantable areas are identified as suitable to interventions of urban forestation. Under Scenario 2 a distribution of suitable census tracts similar to Scenario 1 is observed. Suitable areas are located in peri-urban areas in the Metropolitan City of Cagliari and in urban Centres situated in the Campidano Plain. Spatial clusters of suitable areas are observed in the cities of Olbia and Tempio and in peri-urban districts in the urban areas of Sassari, Nuoro and Oristano. Under scenario 3, derived from prioritising social exposure criterion, a minor portion of plantable areas, equal to 2116,73 ha, is identified as suitable. Suitable areas are concentrated in periu-urban areas in the MCC, and in the urban areas of Sassari and Nuoro, in urbanised clusters in the Campidano Plain and in the cities of Olbia, Tempio and Porto Torres. Lastly, a significant systemic spatial variation is observed for criteria indicators IEM and ICI, as indicated by a local Moran's I statistic equal to, respectively, 0.990 and 0.961, and a mild spatial correlation for the IUF indicator, resulting in a value of 0.246 of the Local Moran's I. In particular, concerning the composite indicator of the magnitude of climate alteration impact, ICI, clusters of observations presenting values above the mean are located in Sassari and Nuoro Provinces, indicating a more relevant estimated alteration of climatic variables in the near future. Concerning urban areas' impact on climate alteration and air quality, formalised by the IEM indicator, clusters of observation presenting values above the mean, representative of elevated concentration of PM10, PM2.5 and Carbon emissions, comprise census tracts in the City of Cagliari, around industrial areas in the metropolitan City of Cagliari and in the urbanised area of the Campidano Plain.

5 Discussion

Several considerations emerge from the study's results. The first consideration concerns the potential benefit in terms of climate alteration mitigation resulting from the reforestation of plantable areas located in suitable urban census tracts. Given a surface area of suitable plantable areas of 3490.113 ha, under Scenario 1, and a carbon sequestration potential of urban forest of 2.67 tCha-1y-1 [38], the total estimated mitigation potential is equal to 9318.60 tCy^{-1}, or to 34168.21 $tCO_2e\ y^{-1}$. Estimated costs of implementing urban forestation interventions are equal to 152 million €, given a unitary cost of 43,485 € ha^{-1} derived from the Program for the conservation and valorisation of urban Green areas financed by the Italian Ministry of Environment and Energy Security (MASE). Under Scenario 2, the total estimated mitigation potential, in terms of Carbon sequestration amounts to 8592.81 tCy^{-1} or to 31506.96 $tCO_2e\ y^{-1}$. Estimated Cost of conversion of areas identified as suitable under Scenario 2 is equal to 140 million €. Under Scenario 3, estimated benefits, in terms of carbon sequestration are equal to 5651.66 tCy^{-1} or to 20722.76 $tCO_2e\ y^{-1}$. Estimated costs of reforestation of suitable areas under Scenario 3 amount to 92 million €.

Concerning suitable locations, an exploratory analysis is conducted by using the Average Comparison Chart function of the GeoDa software tool, Version 1.22. Average

Comparison evaluates the significance of the divergence among the mean value of the j-th variable computed for a sub-set of observations and the mean value computed for the remaining observations. Significance is measured by the p-value derived from the f-statistic calculated for a regression including a binary variable equal to 1 for the observations included in the sub-set and to 0 for the remaining observations. Suitable census tracts, present average values of percentage of plantable areas, tree cover density, carbon emissions and estimated variation in precipitation below the mean of remaining census tracts. Vice versa, normalised indicators of density, concentration of PM10 and PM2.5, increase of minimum and maximum temperatures, and estimated UHI, computed for the suitable areas, present mean values above the mean of the remaining census tracts. As a result, reforestation of areas identified as suitable under Scenario 1 could optimise adaptation co-benefits resulting from improved air quality, micro-climate regulation, and provision of open, multi-purpose urban spaces. Suitable census tracts under Scenario 2 present mean values of Tree Cover Density, Carbon emissions, and reduction of precipitation below the mean of unsuitable census tracts. Vice versa, mean values of percentage of plantable areas, concentration of PM10 and PM2.5, magnitude of UHI conditions, temperature increase, and Surface Urban Heat Island and Land Surface Temperature are above the mean of unsuitable locations. As a result, prioritising reforestation of areas identified as suitable under Scenario 2 could result in optimising adaptation benefits in terms of air and surface temperature regulation and improved air quality. Suitable areas identified under scenario 3 present mean values of tree cover density and carbon emissions below mean values computed for the remaining census tracts, and mean values of percentage of plantable areas, population density, precipitation increase, concentration of PM10 and PM2.5, diurnal UHI conditions, diurnal and nocturnal temperature increase, Surface Urban Heat Island and Land Surface Temperature, above the mean of unsuitable locations. As a result, reforestation of plantable areas situated in suitable locations individuated under scenario 3 could result in optimising adaptation co-benefits related to improved air quality, air and surface temperature regulation, flooding mitigation, and creation of multi-purpose urban spaces.

6 Conclusions

The proposed study is part of a research project on "Geodesign for climate change mitigation and adaptation in the Mediterranean region". Geodesign envisages a structured and iterative process for enabling informed decisions. Geodesign utilises a systems-based perspective to investigate inter-systemic interactions across distinct spatial and temporal scales [2]. As a result, the iterative structure of Geodesign provides a valid tool to address the issues posed by climate alteration [5]. The proposed study aims to develop a procedure for structuring the information required for implementing the Geodesign process in the context of defining strategies of adaptation to and mitigation of climate alteration. The objective is to enable evidence-based decisions related to the localisation of adaptation and mitigation actions for urban areas. The study contributes to the scientific discourse on mitigation and adaptation by investigating the spatial dimension of policies and initiatives aimed at improving the resilience of urbanised areas. More precisely, the original contribution of the study consists in the development of a multi-stage procedure integrating multi-criteria spatial analysis and geostatistical models to enable the identification of

urban lands suitable to the regeneration of urban BGIs. The relevance of the procedure consists in supporting the spatialisation of public policies, optimising the utilisation of limited financial resources and maximising social, economic and environmental benefits. In particular, the study tests and demonstrates the validity of the procedure for identifying suitable locations for urban reforestation interventions so as to maximise benefits in terms of mitigation of climate alteration and co-benefits in terms of adaptation and sustainable development: the conversion of permeable land in areas identified as suitable could result, in fact, in benefits in terms of carbon sequestration ranging from 20722.76 $tCO_2e\ y^{-1}$ under Scenario 3 to 34168.21 $tCO_2e\ y^{-1}$ under Scenario 1. Estimated Adaptation and Sustainable development co-benefits include improved air quality, regulation of air and surface temperature, mitigation of UHI, biodiversity conservation, restoration of ecosystems and creation of inclusive, safe, multi-functional public spaces. The future development of the study will focus on refining the set of indicators related to urban form factors, the impacts of climate alterations on urban areas, and the environmental impact of urbanised areas. It will also concern developing procedures for evaluating land suitability for specific adaptation and mitigation actions relevant to the urban and transport sectors in Mediterranean regions.

Acknowledgments. This study was supported by the research grant for the project "Geodesign for climate change mitigation and adaptation in the Mediterranean region" funded by Fondazione di Sardegna. This study was also partially supported within the "e.INS – Ecosystem of Innovation for Next Generation Sardinia" funded by the Italian Ministry of University and Research under the Next-Generation EU Programme (National Recovery and Resilience Plan – PNRR, M4C2, INVESTMENT 1.5 –DD 1056 of 23/06/2022, ECS00000038). In particular, the "Discussion" was funded by eINS. This study was also partially supported by the MUR through two projects, (1) SMART3R-FLITS: SMART Transport for Travelers and Freight Logistics Integration Towards Sustainability" (Project protocol: 2022J38SR9; CUP Code: F53D23005630006) and (2) PRIN 2022 PNRR project "GeoDesign for Climate URban nEutrality (GD-CURE) - P2022HENAY". This study reflects only the authors' views and opinions, and neither the European Union nor the European Commission nor The MUR can be considered responsible for them.

Disclosure of Interests. The authors have no competing interests.

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