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The Ecological Efficiency of Green Materials in Sustainable Urban Planning—A Model for Its Measurement

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Abstract: Urban green planning is crucial in promoting sustainable urban ecosystems through the mindful use of vegetation, but few approaches are currently able to account for the ecosystem services provided by urban green planning in ex ante planning applications. The present research proposes a methodological approach to sustainable urban planning that accounts for the ecological role of vegetation in urban ecosystems. Indeed, by estimating the functions exerted by different vegetation elements in urban ecosystems through a purposely developed set of equations, the procedure allows for the optimization of the development of urban plans by maximizing the contribution of vegetation to ecosystem dynamics. Specifically, the proposed methodology is articulated in two phases, i.e., the functional role of vegetation is firstly modeled through simple geometric features and specific ecological traits accounting for plant interactions with the environment, and then the selected vegetation traits are used in guiding the choice of the species. The approach has been exemplified through case studies, thereby highlighting its ability to guide planning decisions based on the type, abundance, and spatial organization of vegetation to promote the sustainability of urban development.

Keywords: urban sustainability; urban landscape; vegetation functions; ecological dynamics; ecosystem services

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1. Introduction

Urban sustainability defines a conceptual framework for the development of urban ecosystems satisfying the fundamental principles of economic efficiency, social equity, and environmental integrity [1–4]. Green infrastructures play a crucial role in promoting urban sustainability by supporting the ecological functioning of the urban ecosystem [5,6], with efficiencies that are dependent upon the species assemblages, their spatial configurations, and the adoption of adequate planting and maintenance techniques [7,8]. Specifically, urban green areas act as reservoirs of biodiversity and support processes such as matter cycling, climate mitigation, environmental remediation, soil protection, and improvement of the aesthetic–social–cultural–spiritual spheres of citizens [9–12]. These contributions are usually classified into six groups of functions determining the provision of ecosystem services [13]:

- Ecological: supporting biodiversity and sustaining ecosystem processes;
- Protective: protecting soil in degraded or sensitive areas (riverbanks, embankments, landslide areas, etc.) and mitigating the effects of land degradation and environmental pollution due to anthropogenic activities;

- Hygienic–sanitary: improving the integral health of citizens and promoting recovery during illness [14];
- Social and recreational: supporting recreational and social needs, thereby making the city more comfortable;
- Cultural, educational, and scientific: providing cultural and educational references that promote the harmonious entanglement of people and nature, as well as foster the scientific understanding of the environment;
- Aesthetic–architectural: improving urban landscape structure and scenery.

Considering the crucial role exerted by the spatial configurations of urban green infrastructures, the principles of landscape ecology should arguably guide their planning. Similarly, species ecophysiology should guide the selection of the species and of the associated soils; however, in general, the inclusion of ecological criteria in urban planning is still challenging, and the ecological role of green infrastructures is usually evaluated in ex post contexts only. Such a strategy hinders the optimization of the urban plan aimed at maximizing the ecological efficiency of green infrastructures and, therefore, limits the development of sustainable urban environments. Indeed, urban green planning is mainly managed on a technical prescriptive level as a strategic resource guiding the quality and resilience of the urban environment, which is an approach related to structural limitations in the current legislative reference context [15,16]. However, the urban project must be understood as an inescapable link between urban planning and the environment and, as such, must embrace the ecological dimension in its functional role.

Although several approaches to assess the ecosystem services provided by different land covers can be found in the literature [17,18], very few attempts at including the ecological role of vegetation in urban planning have been made. In particular, attempts at estimating the role of green materials in urban contexts with reference to the specific functions they provide, as well as the proposal of adopting multicriteria approaches in this process, can be found in the works of Fasolino and coworkers [19,20]. Indeed, to act in the direction of settlement quality and sustainability, it is necessary to identify indicators that measure the contribution of green areas to the achievement of these objectives [21–25]. Adopting such a perspective is also crucial to achieve the 17 goals of the 2030 Agenda, with the 11th goal aiming at making cities and human settlements “inclusive, safe, resilient and sustainable” [26]. This goal is divided into 10 specific targets that can be traced back to six main areas of intervention, including green areas and trees, thereby emphasising their pivotal role in making cities liveable and sustainable [27–29]. To maximize the ecological efficiency of green infrastructures, their design should be thus considered early in the urban planning, and the infrastructure itself should not be viewed as a mere aesthetic device or treated as an element detached from the territorial context [30]. To tackle such challenges, the present research aims to develop a procedural framework for the early inclusion of information on vegetation ecological efficiency, quantified through an ensemble of multilevel indicators, into the urban planning process. Such a procedure can be adopted to estimate the resulting efficiency of green infrastructures in urban ecosystems, thus allowing for the ranking different ex ante scenarios and guiding the ecological optimization of sustainable urban plans.

2. Methodological Background

The ecological role of green infrastructures in urban ecosystems can be evaluated in terms of quantifiable functions such as climate mitigation (rainfall interception, evapotranspiration, soil structuring and permeability, etc.), air quality improvement (CO_2 absorption, O_2 release, pollutant trapping, etc.), ecological connectivity enhancement, and biodiversity conservation (ecological corridors, habitat formation, etc.), as well as social benefits (shading, visual and acoustic insulation, wind attenuation, etc.). A brief description of each of these functions is provided thereafter (Sections 2.1–2.4).

2.1. Climate Mitigation

Vegetation in urban environments reduces the overall albedo, i.e., the fraction of solar radiation reflected by surfaces, and shades the soil underneath the canopy, thereby counteracting the heat island phenomenon [22,31,32]. Physical analysis on the effects of vegetation on microclimate, to date, has focused mostly on single trees or regular arrangements of trees in parks, especially through computational fluid dynamics modeling [33,34], thus demonstrating a significant contribution of vegetation to the heat transfer balance that is dependent upon crown shape and tree arrangement. The control of the energy balance in urban ecosystems [35–37] is also exerted by vegetation through transpiration, thereby resulting in the release of water vapor and latent heat into the atmosphere [38], which has important consequences for air circulation. Furthermore, vegetation is also able to contribute to the regulation of the hydrological cycle through both its epigeous and hypogeous structures. Indeed, leaves, branches, and trunks intercept rainfall and delay the arrival of precipitation on the ground [39–42], thus affecting the energy distribution of raindrops through an overall reduction in their kinetic energy and, therefore, in their capability to displace soil particles. Such a displacement, which is mainly responsible for soil erosion, is also promoted by rainwater surface runoff, which is reduced by soil permeability and by the development of the root system, thereby hampering water flow and promoting its infiltration into the soil. The architecture of the root system [43,44] also contributes to the stabilization of slopes, thus providing a fundamental role in reducing the risk of landslides and, in general, of hydrogeological instability.

2.2. Air Quality Improvement

Vegetation is able to improve air quality through photosynthesis and absorption/adsorption processes, thus contributing, respectively, to the sequestration of CO_2/release of O_2, as well as the removal of pollutants [45,46]. The importance of these effects is such that urban and periurban green belts have long been advocated for improving the quality of the urban environment [15,16,27,47]. For example, several studies evaluated the aerodynamic effects of trees on pollutant concentrations in road canyons using wind tunnel experiments and numerical simulations [11,48–51], thereby highlighting the substantial contribution of trees in preventing the dispersion of air pollutants [52–54]. The capability to intercept particulate matter and accumulate several organic and inorganic pollutants allows for using urban vegetation not only in bioremediation [55], but also in biomonitoring applications [56–58].

2.3. Ecological Connectivity Enhancement and Biodiversity Conservation

From a landscape ecology perspective, green areas represent patches of natural habitats supporting biodiversity in urban ecosystems, which are surrounded by hostile matrices that limit movements and dispersion [12]. Moreover, more complex green areas, which are formed by diverse communities and several layers of vegetation, further promote their biodiversity through the availability of diversified ecological niches. Even small patches of vegetation, such as tree rows, may serve as continuous or discontinuous ecological corridors that improve the connectivity among larger patches, such as urban parks and periurban areas, thereby sustaining organism movements and supporting metapopulation dynamics. In this context, ecological corridors have long been identified as invaluable conservation tools to counteract landscape fragmentation and maintain biodiversity by providing links or restoring connections between isolated ecological spaces in human-modified landscapes [59]. As such, the establishment of green areas aimed at building ecological corridors represents a focal aspect of urban ecological planning [60–63], and it should be optimized while taking ecological, social, and economic benefits into account [64].

2.4. Social Benefits

Spatial delimitation is a prerogative of urban green that is inherent in its etymology: the word “garden” derives from the French jardin (“closed place”), which in turn is derived from the Gothic gart (“enclosure”). The perception of boundaries and of the external space is influenced by the morphology of the landscape [65]. It is a concept that is closely linked to that of a barrier, i.e., the visual and acoustic separation between areas with different and incompatible uses. For example, hedges or shrubs acting as traffic dividers reduce the impact of headlights at night and of noise, thereby enhancing drivers' safety and improving citizens' life in residential areas [66,67]. Similarly, perimeter hedges and shrubs surrounding urban parks offer privacy to people spending time in the parks beyond just isolating the parks from the urban environment [68]. In this context, the reflective and absorptive properties of plants, as well as the damping effects produced by the air within crowns and between plants and buildings, make them a potentially suitable alternative to traditional acoustic barriers, especially in the lower frequency range [69], in addition to their aesthetic–architectural value [70,71]. Moreover, the natural attenuation of wind offered by green areas constitutes an additional function of vegetation in urban environments. Indeed, vegetation is effective in reducing wind speed and redirecting air flows, whose understanding is possible primarily through the use of computational fluid dynamics models [72].

3. Methodology

The proposed approach relies on identifying a suitable set of indices for the different, quantifiable functions exerted by vegetation in urban ecosystems and on defining a suitable normalization measure to make the results commensurable. In order to guarantee a large leeway in optimizing the structure of urban green areas, the indices mainly rely on simple geometrical measures (Table 1) such as plant number, as well as size or area occupied, thereby allowing for the identification of shapes and their spatial arrangement to maximize ecosystem services provided by vegetation. In addition, morphological and physiological attributes (Table 1) can be used to associate particular characteristics (e.g., broadleaved/coniferous, clumped/regular, deciduous/evergreen vegetation, etc.) to the shapes and finely tune the choice of green elements. In this context, the leaf area index (LAI), defined as the ratio of total leaf area to ground area [73], appears in most of the proposed indices. Indeed, LAI relates to several processes at the interface between the active photosynthesizing surfaces of plants and their surrounding environment, such as shading, CO_2 absorption and storage, pollutant absorption, climate mitigation, and rainfall interception. Morphological and physiological parameters allow for associating shapes to particular species, with an additional layer of details introduced later in the planning process. The maximization function relies on the weighted average of the indices, which are grouped into different classes in relation to the specific functions that the different indices are meant to measure. Such groups are defined as the weighted average of particular indices and allow for differentially weighting the desired ecological functions in relation to urban lot destinations. Ultimately, the method involves three information layers at different levels of detail/synthesis, with a weighted average function allowing for moving across the layers. To simplify the description and ensure consistency thereafter, indices are referred to as specific goals (SGs), groups identifying ecological functions as intermediate goals (IGs) and the value identifying the overall ecological performance of urban green areas in urban lots as the global goal (GG). Normalization of SGs, allowing the calculation of IGs, is obtained through index scaling in the unit interval.

Specifically, after identifying the specific areas allocated to green areas, 10 SGs (Table 2) are calculated, which are grouped into 4 IGs, and a final GG is obtained. In terms of SGs, with the exception of the index of permeability, derived from an equation customarily adopted in the Italian planning context, all the indices are original contributions to the evaluation of vegetation functionality in urban environments.

The described three-level structure, in terms of SGs, IGs, and GG, allows for associating a single value of estimated ecological efficiency, and its functional breakdown, to a selected development plan for each lot. The obtained information can be combined to estimate the overall efficiency of an urban plan by averaging GGs of different lots into an overall green efficiency index (EI_{green}). In this framework, maximization of urban green efficiency can be attained through either the concomitant definition of alternative planning scenarios and the selection of the one scoring the highest EI_{green} or by identifying critical functions, by inspecting IGs and SGs values, that need optimization to increase the EI_{green} value.

In terms of the SGs reported in Table 2, the permeability ratio, defined as the simple ratio between the overall unbuilt and unpaved areas to the total area, allows for estimating the area suitable for the infiltration of rainwater into the ground. Although it does not quantify a specific function of vegetation, it is included in the estimation of the overall efficiency of green materials due to the role it exerts on the definition of urban plans.

Rainfall interception, in terms of the reduction in the free fall of raindrops, can be approximated by the canopy cover fraction, i.e., the projection of the canopy on a horizontal surface, which can, in turn, be approximated using the formulation equivalent to the Lambert–Beer law [74,75]. The extinction coefficient kw in this case can be taken as $kw_i = 0.7$ [41]. The index does not consider the storage of water into the canopy and the secondary precipitations due to the quality and quantity of the data required to estimate these processes at the plant level, but rather, it allows for estimating the effects of canopies in reducing the kinetic energy of raindrops.

Table 1. Parameters considered in the definition of the indices quantifying the functions exerted by vegetation in urban environments. For each parameter, the meaning and the usual values (where applicable) are provided.

Parameter	Description	Characteristic Value	
i	ith element of vegetation		
N	Number of vegetation elements		
G	Lot area		
G_i	Area occupied by i		
G_p	Permeable area		
G_s	Semipermeable area		
ϕ_s	Permeability coefficient	$\phi_s = 0.5$ *, $\phi_s \in]0,1[$	
$p_i = \frac{G_i}{G}$	Fraction of G occupied by i	$p_i \in [0,1]$	
h	Height of the tallest vegetation layer		
S_i	Number of stems		
$\bar{D}_i$	Average crown diameter		
$\Omega_i = \left(\frac{S_i \bar{D}_i}{\sqrt{G_i}}\right)^{0.7}$	Clumping factor		[76]
$v_{i\parallel w}$	Volume of linear green elements parallel to w [1]		
ρ_i	Vegetation density	$\rho_i = 0.7$ *, $\rho_i \in [0,1]$	
$\bar{d}$	Average distance among green elements [2]		
$d_{i\perp w}$	Vegetation distance from w		
L_i	Leaf area index	$L_i = 3$ *, $L_i \in [0, 23.5]$	[77,78]
k_i	Extinction coefficient for direct radiation	$k_i = 0.6$ *, $k_i \in [0.2, 0.8]$	[79]
kd_i	Extinction coefficient for diffuse radiation	$kd_i = 0.8$ *, $kd_i \in [0.5, 1]$	[80]
kw_i	Extinction coefficient for rainfall interception	$kw_i = 0.7$ *, $kw_i \in [0.5, 1]$	[41]
ϵ	Efficiency of photosynthesis conversion	$\epsilon = 0.02$ *, $\epsilon \in [0.01, 0.03]$	[80]
ζ	Particulate interception capability	$\zeta_{conifer} \approx 5 \cdot \zeta_{broadleaf}$ [3]	[78]
τ	Insulation effect at increasing $d_{i\perp w}$	$\tau = 1$ *, $\tau \in [0, \infty]$	
λ	Isolation effect at increasing $\bar{d}$	$\lambda = 1$ *, $\lambda \in [0, \infty]$	
Φ_i	Photosynthetically active radiation	$\Phi_i \in [0,1]$	
C_d	Drag coefficient	$C_d \approx 0.2$	[81]
α	Roughness of the underlying surface	$\alpha \approx 1.5$, $\alpha \in [1,2]$	[81]
k	von Karman constant	$k = 0.41$	[80]
$\beta = \frac{4C_d L_i}{\alpha^2 k^2}$	Attenuation factor		[81]

* Value used in the calculations. [1] w indicates vertical surfaces (e.g., walls). [2] Distance is calculated considering neighboring lots. [3] ζ has been assumed equal to 0.1 for broadleaves and to 0.5 for conifers in the calculations.

The transpiration of vegetation defines its contribution to evapotranspiration, which depends on the fraction of energy intercepted by leaves, which is related to the LAI and the height of vegetation through the Lambert–Beer law [80]. In the case of layered vegetation, the incident radiation varies among the layers due to the absorption by the upper layers of vegetation. As such, the incident radiation (Φ_i), which for the sake of comparisons among different scenarios can be imposed equal to 1 in the case of the uppermost layer, should be reduced for the layers underneath according to the fraction of light absorbed by the overshadowing layers. In general, $\Phi_i = 1 - f_{j,\ldots,z}$, where $f_{j,\ldots,z}$, defines the fraction of light absorbed by the jth, ..., zth vegetation layers above the considered one.

Table 2. Equations defining the specific goals (SGs) and their grouping into different intermediate goals (IGs). The parameters appearing in the equations are reported, along with their meaning and common values, in Table 1.

Intermediate Goal	**Specific Goal**	**Equation**
Urban Climate (UC)	Permeability	$P = \frac{G_p + \phi_s G_s}{G}$
	Rainfall interception	$Ri = \sum_{i=1}^{N} \left(1 - e^{-kw_i L_i \Omega_i}\right) \cdot p_i$
	Transpiration	$T = \sum_{i=1}^{N} \left(\Phi_i \left[1 - e^{-kd_i L_i \Omega_i}\right]\right) \cdot p_i$
Air Quality (AQ)	Photosynthesis	$A = \sum_{i=1}^{N} \left(\epsilon \Phi_i \left[1 - e^{-kd_i L_i \Omega_i}\right]\right) \cdot p_i$
	Particulate interception	$Pi = \sum_{i=1}^{N} \left(\zeta L_i h \frac{\cosh(\beta) - 1}{\beta \sinh(\beta)}\right) \cdot p_i$
Biodiversity (B)	Environmental diversity	$H = -\sum_{i=1}^{N} p_i \ln p_i$
	Ecological connectivity	$Ec = e^{-\lambda \bar{d}}$
Comfort (C)	Shading	$S = \sum_{i=1}^{N} \left(1 - e^{-k_i L_i \Omega_i}\right) \cdot p_i$
	Wind attenuation	$Wa = h \cdot \frac{\beta \sinh(\beta) - \cosh(\beta) + 1}{\beta \sinh(\beta)}$
	Acoustic and visual insulation	$I = \sum_{i=1}^{N} \rho_i v_{i\|w} e^{-\tau d_{i \perp w}}$

Photosynthesis, O_2 release, and CO_2 sequestration are linearly related to the fraction of absorbed light, which depends on the LAI and the extinction coefficient for scattered light kd [80]. As for the estimation of transpiration, the contribution of each vegetation layer to the overall photosynthesis/O_2 release/CO_2 sequestration should be scaled according to the fraction of incident light, which depends on the absorption by the overshadowing layers.

Particulate interception is proportional to LAI, wind speed, and the characteristic interception capacity of coniferous and broadleaf trees [78]. The effect of wind speed appears in the equation in the form of the integral of the Cowan vertical velocity profile [81] over h, the height of the tallest element of vegetation, thus taking into account the energy dissipation of wind blowing through the leaves.

The effect of vegetation on biodiversity is considered proportional to the diversity of ecological niches, which, in turn, is dependent upon the diversity of microenvironments formed by vegetation [82–84]. Hence, the diversity of the elements of vegetation, described using the Shannon–Wiener index [82], is considered as a measure of the effects of green materials on biodiversity. To this end, the index is calculated from the relative abundances of different green elements, which are identified based upon morphological, phenological, or taxonomical criteria that should be used consistently in the evaluation of different scenarios.

Adopting an island biogeography perspective [85], the likelihood of successful movements of animals among different green patches in an urban environment is considered dependent upon the distance among patches. The proposed formulation describes the movement in terms of exponential dispersal [85] controlled by the average distance $\bar{d}$ between vegetation elements within a plot and between neighboring plots. The index purposely focuses on the effect of distance only, thereby avoiding any reference to the effects of matrix permeability. The choice is dictated by the need to provide an overall estimate of environmental connectivity without any reference to specific taxa, whose movement capabilities affect matrix permeability.

Shading can be approximated by the canopy cover fraction, i.e., the projection of the canopy onto a horizontal surface, which in turn can be described using a formulation that is equivalent to the Lambert–Beer law [80]. The extinction coefficient for direct radiation k_i can be estimated using geometric models and can be interpreted as the density of light intercepting elements (mainly leaves and branches) within the canopy.

Wind attenuation due to the energy dissipation in passing through vegetation can be described in terms of the difference between the vertical integral of the wind speed over bare ground, which is assumed constant up to an elevation corresponding to the height of the vegetation, and the integral of the Cowan vertical velocity profile [81]. Although the assumption of a constant vertical velocity profile over bare ground represents a coarse approximation, due to the friction over surfaces, it serves in the equation as a simple reference to make the index increase with the reduction in wind velocity due to vegetation. For the sake of comparison, the wind speed above the vegetation is considered equal to 1.

The insulating effect of vegetation against walls and other vertical surfaces w depends on the area of vegetation projected onto w and its width, on the permeability of the vegetation to the sight and sound/noise, which is expressed as the reciprocal of the fraction of vegetation gaps (i.e., density), and on the distance between vegetation and w. The relationship between insulation and distance has been assumed to be exponential.

4. Case Study

With a view to exemplify the proposed procedure, different planning scenarios varying in the quality, quantity, and distribution of green materials have been simulated on an area in the municipality of Fisciano, which is a small town in the province of Salerno in Southern Italy (Figure 1). The area of 245,166 m^2 is bordered to the south and east by highways and to the north and west by municipal roads. It is mostly surrounded by residential, industrial, and agricultural sites, including a service area pertaining to the University of Salerno. Excluding roads, it is possible to identify 18 lots with different destinations: residential, commercial, social spaces, and urban facilities, with the latter including green areas (Figure 1 and Table 3).

In terms of the simulations of the proposed methodology, a reference scenario (S_0) was defined using an approach to the use of greenery aimed at improving the aesthetic and architectural values of private spaces, as well as the scenery of public spaces, thereby focusing on minimizing the visual impact from buildings. The reference scenario was then modified to obtain two additional scenarios (S_1 and S_2) aimed at maximizing the different ecological functions exerted by vegetation. Such a procedure exemplifies one of the potential approaches in using the proposed methodology to improve the ecological performance of urban green planning, i.e., maximizing the GGs by identifying the SGs/IGs needing optimization through consecutive iterations. Alternatively, EI_{green} represents a suitable index to rank several candidate scenarios, thereby allowing for the choice of the one scoring the highest value.

In order to provide a straightforward exemplification of the procedure, the scenarios have been purposely simplified by including a limited diversity of green elements, i.e., hedges, bushes, and trees of different sizes, with the same physiological parameters (Table 1) and avoiding stratified vegetation. Although the scenarios admittedly lack the nuances of more sophisticated urban green plans, not only they are able to represent several real case situations with limited leeway in the choice of urban green elements, but they can be straightforwardly expanded to more complex cases, such as those commonly encountered in tropical regions. Especially in these cases, the possibility to tune several parameters that account for the different interactions of green elements with the environment (including other plants in stratified communities) becomes crucial in accurately estimating the benefits of vegetation in urban ecosystems.

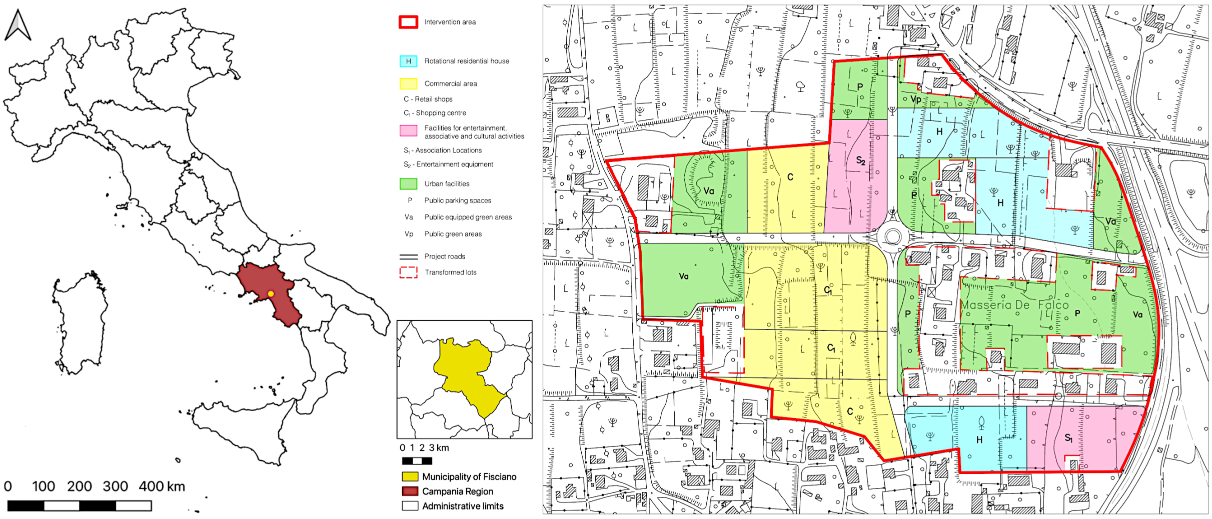

Figure 1. The area selected for the case study (dark yellow) within the regional (dark red) and national context (outline), with indication of the defined lots and their destinations highlighted in different colors.

Table 3. Destinations and characteristics of identified lots, including the area uncovered by buildings (G_u and $G_{u\%}$, with the latter expressed as percentage of the total area). Abbreviations for the various parameters are reported in Table 1.

Lot	Type	G	G_u	$G_{u\%}$	G_p	G_s
Sv [1]	Viability	15,763.0	15,763.0	100.0	0.0	0.0
H1	University residence	10,459.0	7853.0	75.1	4450.0	1387.5
H2	University residence	11,237.0	8491.0	75.6	4756.0	1512.5
H3	University residence	10,565.0	7901.0	74.8	4523.0	1750.0
C	Retail shop	10,669.0	7130.0	66.8	4534.0	1362.5
C	Retail shop	10,569.0	7646.0	72.3	4520.0	1137.5
C1	Shopping center	19,207.0	12,947.0	67.4	7883.0	2387.5
C1	Shopping center	10,900.0	7452.0	68.4	4595.0	1337.5
S1	Social space	10,616.0	6782.0	63.9	4428.0	1137.5
S2	Open-air theater	10,340.0	7720.0	74.7	4373.0	1575.0
Sstp1	Public parking	5046.0	5046.0	100.0	2341.0	725.0
Sstp2	Public parking	3401.0	3401.0	100.0	1767.0	750.0
Sstp3	Public parking	3853.0	3853.0	100.0	1872.7	425.0
Sstp4	Public parking	15,753.0	15,753.0	100.0	6671.0	2500.0
Sstv1	Public green area	9305.0	9305.0	100.0	3950.7	0.0
Sstv2	Public green area	11,288.0	11,288.0	100.0	6648.4	0.0
Sstv3	Public green area	4838.0	4838.0	100.0	2721.5	0.0
Sstv4	Public green area	11,210.0	11,210.0	100.0	7325.0	0.0
Sstvp	Public green area	2430.0	2430.0	100.0	2417.0	0.0

[1] Sv was customarily excluded from the urban green planning.

For each scenario, the fundamental parameters associated with the planning of green areas, i.e., the number of bushes (n_b), the number, length, area, and volume of hedges (n_h, l_h, A_h, V_h, respectively), and the number of 1st ($h > 15$ m), 2nd (9 m $< h <$ 15 m), and 3rd ($h < 9$ m) class trees (n_{1ct}, n_{2ct}, and n_{3ct}, respectively), are reported in Table 4. In particular, in moving from S_0 to S_2, the number of bushes reduces and the number of hedges and trees increases, especially for large size trees (Figure 2). Moreover, with respect to S_0, S_1 was designed to increase the coverage of green materials by adopting a minimum permeability ratio of 0.40 and a minimum tree planting index of 20 trees per ha.

Table 4. Urban green planning characteristics per lot in the different scenarios, with indication of the cumulative values (Σ) in each scenario. Parameter definitions are provided in the text (Section 4).

Scenario	Lot	n_b	n_h	l_h	A_h	V_h	n_{1ct}	n_{2ct}	n_{3ct}
S_0	H1	4	2	46.4	23.2	34.8	0	5	4
	H2	3	1	90.2	45.1	67.6	0	2	2
	H3	5	1	78.4	39.2	58.8	0	3	3
	C	3	1	104.0	52.0	78.0	0	5	2
	C	4	2	116.1	58.0	87.1	0	3	2
	C1	4	2	65.6	32.8	49.2	0	4	3
	C1	4	2	47.2	23.6	35.4	0	1	2
	S1	5	1	47.2	23.6	35.4	0	2	4
	S2	5	1	59.4	29.7	44.5	0	6	2
	Sstp1	3	0	0.0	0.0	0.0	0	4	3
	Sstp2	2	0	0.0	0.0	0.0	0	4	5
	Sstp3	10	0	0.0	0.0	0.0	0	0	0
	Sstp4	0	0	0.0	0.0	0.0	0	0	4
	Sstva1	5	0	0.0	0.0	0.0	0	3	3
	Sstva2	3	1	75.3	37.7	56.5	0	4	4
	Sstva3	5	0	0.0	0.0	0.0	0	3	4
	Sstva4	7	1	37.1	18.5	27.8	0	3	11
	Sstvp	3	0	0.0	0.0	0.0	0	6	3
S_1	H1	0	3	173.4	86.7	130.0	12	6	3
	H2	0	3	159.3	79.6	119.4	10	8	5
	H3	0	3	215.1	107.6	161.3	9	8	5
	C	0	3	149.8	74.9	112.4	10	9	3
	C	0	4	265.3	132.7	199.0	9	9	4
	C1	0	5	247.4	123.7	185.6	10	10	19
	C1	0	2	50.5	25.2	37.8	7	4	11
	S1	0	3	183.6	91.8	137.7	5	5	12
	S2	0	5	247.5	123.8	185.6	11	6	4
	Sstp1	0	0	0.0	0.0	0.0	6	5	0
	Sstp2	0	2	142.8	71.4	107.1	6	1	0
	Sstp3	0	0	0.0	0.0	0.0	7	1	0
	Sstp4	0	0	0.0	0.0	0.0	7	0	25
	Sstva1	0	0	0.0	0.0	0.0	10	9	0
	Sstva2	0	1	90.6	45.3	67.9	16	7	0
	Sstva3	0	1	70.2	35.1	52.7	8	2	0
	Sstva4	0	1	38.0	19.0	28.5	17	6	0
	Sstvp	0	0	0.0	0.0	0.0	0	5	0
S_2	H1	0	3	260.1	130.0	195.0	11	48	3
	H2	0	3	159.3	79.6	119.4	4	18	8
	H3	0	3	430.7	215.3	323.0	23	30	0
	C	0	3	149.8	74.9	112.4	16	12	0
	C	0	4	265.3	132.7	199.0	2	17	5
	C1	0	3	247.1	123.6	185.3	55	0	13
	C1	0	2	50.5	25.2	37.8	12	2	8
	S1	0	3	389.9	194.9	292.4	37	27	11
	S2	0	3	247.9	123.9	185.9	4	17	4
	Sstp1	0	1	60.4	30.2	45.3	8	2	14
	Sstp2	0	3	214.7	107.4	161.0	23	0	10
	Sstp3	0	4	368.8	184.4	276.6	38	0	42
	Sstp4	0	1	8.0	4.0	6.0	68	24	19
	Sstva1	0	3	90.8	45.4	68.1	11	18	0
	Sstva2	0	4	212.4	106.2	159.3	26	47	0
	Sstva3	0	1	180.3	90.2	135.2	33	12	0
	Sstva4	0	4	331.7	165.9	248.8	39	32	13
	Sstvp	0	2	59.4	29.7	44.5	0	14	0
S_0	Σ_0	75	15	766.8	383.4	575.1	0	58	61
S_1	Σ_1	0	36	2033.2	1016.6	1524.9	160	101	91
S_2	Σ_2	0	50	3726.9	1863.5	2795.2	410	320	150

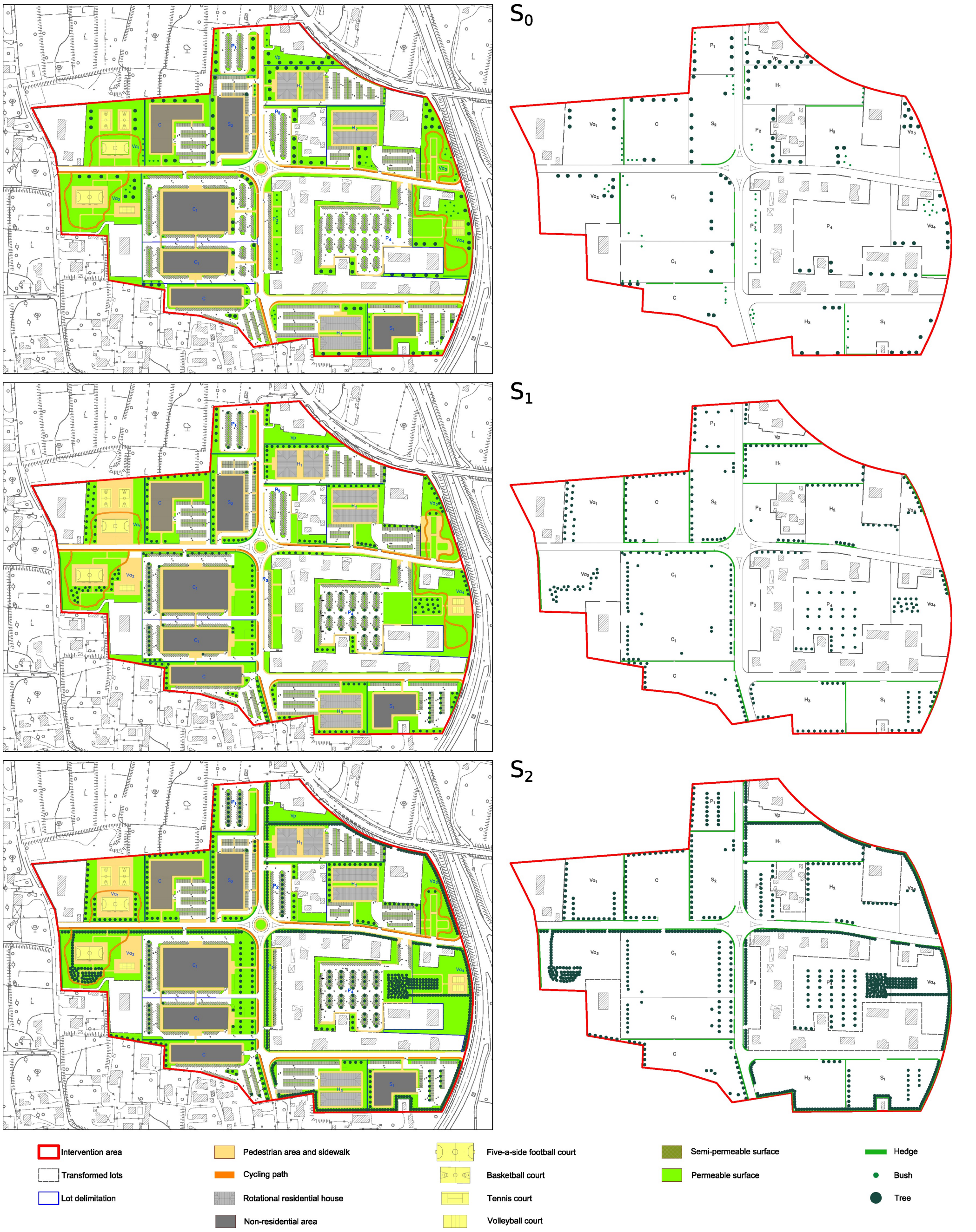

Figure 2. Illustration of the urban green planning in the S_0, S_1, and S_2 scenarios (**left**). The type, number, and spatial arrangement of green elements are also highlighted (**right**).

S_2 was then planned by focusing specifically on the spatial arrangement of green materials, thereby striving to minimize their respective distance and, therefore, maximize the ecological connectivity through green corridors. From the data in Table 4 and the values reported in Table 1 for the parameters specifying the attributes of the different green materials, the SGs for each lot were calculated according to the equations in Table 2 and are reported in Table 5. The SG values were then scaled to the unit interval and averaged for each lot and each scenario into the IG values reported in Table 5. The latter were finally averaged into a single GG value for each lot using identical weights for the different IGs (Table 5). The resulting EI_{green} value for each scenario, obtained as the arithmetic average of the GG values associated with the different lots, clearly indicates an improvement in the overall ecological efficiency moving from S_0 (EI_{green0} = 0.13) to S_1 (EI_{green1} = 0.33) to S_2 (EI_{green2} = 0.54).

Table 5. SG, IG, and GG values per lot for the different scenarios. IGs are calculated from SGs scaled in the unit interval. EI_{green} values for S_0, S_1, and S_2 are also reported.

Scenario	Lot	*P*	*Ri*	*T*	*A*	*Pa*	*H*	*Ec*	*S*	*Wa*	*I*	UC	AQ	B	C	GG
S_0	H1	0.41	0.07	0.07	1.46	0.05	0.25	0.00	0.07	14.29	1.18	0.13	0.04	0.13	0.21	0.13
	H2	0.40	0.04	0.04	0.70	0.02	0.17	0.00	0.03	14.29	13.71	0.11	0.02	0.08	0.28	0.12
	H3	0.39	0.05	0.05	1.06	0.03	0.22	0.00	0.05	14.29	14.10	0.11	0.03	0.11	0.28	0.13
	C	0.41	0.07	0.07	1.47	0.05	0.25	0.00	0.07	14.29	14.54	0.13	0.04	0.13	0.29	0.15
	C	0.31	0.07	0.07	1.37	0.04	0.26	0.00	0.06	14.29	21.26	0.09	0.04	0.13	0.33	0.15
	C1	0.20	0.07	0.07	1.35	0.04	0.20	0.00	0.06	14.29	0.01	0.04	0.04	0.10	0.21	0.10
	C1	0.17	0.05	0.05	0.94	0.03	0.16	0.00	0.04	14.29	0.01	0.02	0.03	0.08	0.20	0.08
	S1	0.31	0.05	0.05	0.98	0.03	0.18	0.00	0.04	14.29	6.72	0.08	0.03	0.09	0.24	0.11
	S2	0.32	0.11	0.11	2.11	0.07	0.26	0.00	0.10	14.29	1.06	0.11	0.07	0.14	0.22	0.13
	Sstp1	0.46	0.10	0.10	1.99	0.07	0.28	0.00	0.10	14.29	0.00	0.17	0.06	0.15	0.21	0.15
	Sstp2	0.52	0.15	0.15	2.96	0.10	0.37	0.00	0.14	14.29	0.00	0.21	0.09	0.20	0.23	0.18
	Sstp3	0.49	0.00	0.00	0.05	0.00	0.02	0.00	0.00	0.84	0.00	0.13	0.00	0.00	0.00	0.03
	Sstp4	0.25	0.01	0.01	0.23	0.00	0.06	0.00	0.01	6.53	0.00	0.03	0.00	0.02	0.08	0.04
	Sstva1	0.73	0.03	0.03	0.51	0.02	0.12	0.00	0.02	14.29	0.00	0.24	0.02	0.05	0.20	0.13
	Sstva2	0.71	0.04	0.03	0.68	0.02	0.15	0.00	0.03	14.29	0.00	0.23	0.02	0.07	0.20	0.13
	Sstva3	0.80	0.05	0.05	1.00	0.03	0.19	0.00	0.05	14.29	0.00	0.28	0.03	0.09	0.20	0.15
	Sstva4	0.72	0.04	0.04	0.73	0.02	0.16	0.00	0.03	14.29	0.00	0.24	0.02	0.08	0.20	0.13
	Sstvp	0.99	0.14	0.14	2.77	0.10	0.33	0.00	0.14	14.29	0.00	0.40	0.09	0.17	0.22	0.22
S_1	H1	0.43	0.40	0.40	7.97	0.42	0.66	0.01	0.40	24.30	17.69	0.30	0.30	0.37	0.53	0.38
	H2	0.42	0.35	0.35	7.01	0.35	0.68	0.01	0.35	24.30	11.62	0.28	0.26	0.38	0.49	0.35
	H3	0.43	0.35	0.35	7.00	0.34	0.70	0.01	0.35	24.30	12.64	0.28	0.26	0.39	0.49	0.36
	C	0.42	0.37	0.37	7.44	0.37	0.68	0.00	0.37	24.30	22.17	0.29	0.28	0.38	0.55	0.37
	C	0.43	0.36	0.36	7.28	0.35	0.72	0.01	0.36	24.30	58.06	0.29	0.27	0.40	0.76	0.43
	C1	0.41	0.25	0.25	5.06	0.23	0.63	0.00	0.25	24.30	0.44	0.22	0.18	0.34	0.40	0.29
	C1	0.42	0.25	0.25	5.00	0.25	0.57	0.01	0.25	24.30	0.01	0.23	0.19	0.32	0.39	0.28
	S1	0.42	0.24	0.24	4.77	0.21	0.62	0.00	0.24	24.30	2.37	0.22	0.17	0.34	0.41	0.28
	S2	0.42	0.39	0.39	7.83	0.40	0.69	0.00	0.39	24.30	12.98	0.30	0.29	0.38	0.51	0.37
	Sstp1	0.46	0.40	0.40	7.94	0.42	0.60	0.00	0.40	24.30	0.00	0.32	0.30	0.33	0.43	0.34
	Sstp2	0.52	0.45	0.45	9.00	0.48	0.60	0.02	0.45	24.30	0.00	0.37	0.35	0.35	0.45	0.38
	Sstp3	0.49	0.45	0.45	8.94	0.52	0.46	0.00	0.44	24.30	0.00	0.35	0.36	0.25	0.44	0.35
	Sstp4	0.42	0.17	0.17	3.31	0.16	0.40	0.01	0.16	24.30	0.00	0.18	0.12	0.23	0.37	0.23
	Sstva1	0.42	0.40	0.40	8.01	0.42	0.61	0.00	0.40	24.30	0.00	0.30	0.30	0.33	0.43	0.34
	Sstva2	0.59	0.33	0.33	6.63	0.36	0.54	0.02	0.33	24.30	0.00	0.33	0.26	0.32	0.42	0.33
	Sstva3	0.56	0.38	0.38	7.61	0.42	0.54	0.01	0.38	24.30	0.00	0.35	0.30	0.31	0.43	0.35
	Sstva4	0.65	0.31	0.31	6.11	0.34	0.50	0.03	0.30	24.30	0.00	0.35	0.24	0.30	0.41	0.32
	Sstvp	0.99	0.10	0.10	2.08	0.07	0.24	0.03	0.10	14.29	0.00	0.38	0.07	0.15	0.22	0.20
S_2	H1	0.43	0.86	0.86	17.15	0.72	0.83	0.52	0.86	24.30	17.69	0.53	0.59	0.96	0.65	0.68
	H2	0.42	0.32	0.32	6.44	0.26	0.69	0.02	0.32	24.30	11.62	0.26	0.22	0.39	0.48	0.34
	H3	0.43	0.96	0.96	19.12	0.92	0.83	0.48	0.96	24.30	29.48	0.58	0.70	0.91	0.74	0.74
	C	0.42	0.55	0.55	10.97	0.57	0.70	0.02	0.55	24.30	22.17	0.38	0.42	0.40	0.60	0.45
	C	0.43	0.28	0.28	5.62	0.21	0.63	0.02	0.28	24.30	58.06	0.24	0.18	0.36	0.74	0.38
	C1	0.46	0.74	0.74	14.87	0.85	0.38	0.46	0.74	24.30	0.44	0.49	0.59	0.64	0.52	0.56
	C1	0.42	0.34	0.34	6.83	0.38	0.56	0.01	0.34	24.30	0.01	0.27	0.27	0.31	0.42	0.32
	S1	0.42	1.33	1.33	26.52	1.36	0.66	0.52	1.32	24.30	18.37	0.77	1.00	0.86	0.77	0.85
	S2	0.42	0.34	0.34	6.74	0.27	0.71	0.01	0.34	24.30	12.98	0.27	0.23	0.40	0.49	0.35
	Sstp1	0.46	0.52	0.52	10.30	0.53	0.75	0.01	0.51	24.30	0.00	0.38	0.39	0.42	0.46	0.41
	Sstp2	0.67	0.70	0.70	14.04	0.75	0.61	0.18	0.70	24.30	0.00	0.55	0.54	0.51	0.51	0.53
	Sstp3	0.43	1.05	1.05	20.92	0.91	0.91	0.46	1.05	24.30	0.00	0.63	0.73	0.94	0.60	0.72
	Sstp4	0.42	0.90	0.89	17.90	0.94	0.70	0.01	0.89	24.30	0.00	0.55	0.69	0.39	0.56	0.55
	Sstva1	0.42	0.56	0.56	11.10	0.53	0.75	0.01	0.55	24.30	0.00	0.38	0.41	0.43	0.47	0.42
	Sstva2	0.59	0.81	0.81	16.27	0.77	0.79	0.39	0.81	24.30	0.00	0.58	0.59	0.81	0.54	0.63
	Sstva3	0.80	1.15	1.15	23.01	1.26	0.41	0.44	1.15	24.30	0.00	0.83	0.90	0.64	0.62	0.75
	Sstva4	0.67	0.84	0.84	16.83	0.86	0.81	0.45	0.84	24.30	0.00	0.63	0.63	0.88	0.54	0.67
	Sstvp	0.99	0.30	0.30	6.05	0.21	0.41	0.42	0.30	14.29	0.00	0.48	0.19	0.63	0.27	0.39
S_0	EI_{green0}															0.13
S_1	EI_{green1}															0.33
S_2	EI_{green2}															0.54

In spite of the overall estimate of ecological efficiency derived using EI_{green}, the (scaled) SG matrix provides a mean to evaluate the contribution of each SG to the differentiation of the scenarios, i.e., to identify which ecological functions are maximized by the different urban green planning scenarios. To this end, multivariate ordination techniques such as discriminant analyses (e.g., LDA) can be adopted and possibly coupled to inferential approaches such as multivariate analysis of variance (MANOVA) to provide statistical support to the hypothesis of a differentiation in planning scenarios based on their ecological efficiency.

In the case of S_0, S_1, and S_2, such an approach indicated significant (Pillai's trace = 1.345, $p < 0.001$) differences in the ecological functionalities among scenarios, with S_1 and S_2 being mostly differentiated from S_0 by the highest values of wind attenuation and biodiversity (Figure 3). Moreover, S_2 is clearly differentiated from S_1 by the highest values of most of the other SGs, especially the ecological connectivity and the improvement of air quality (Figure 3).

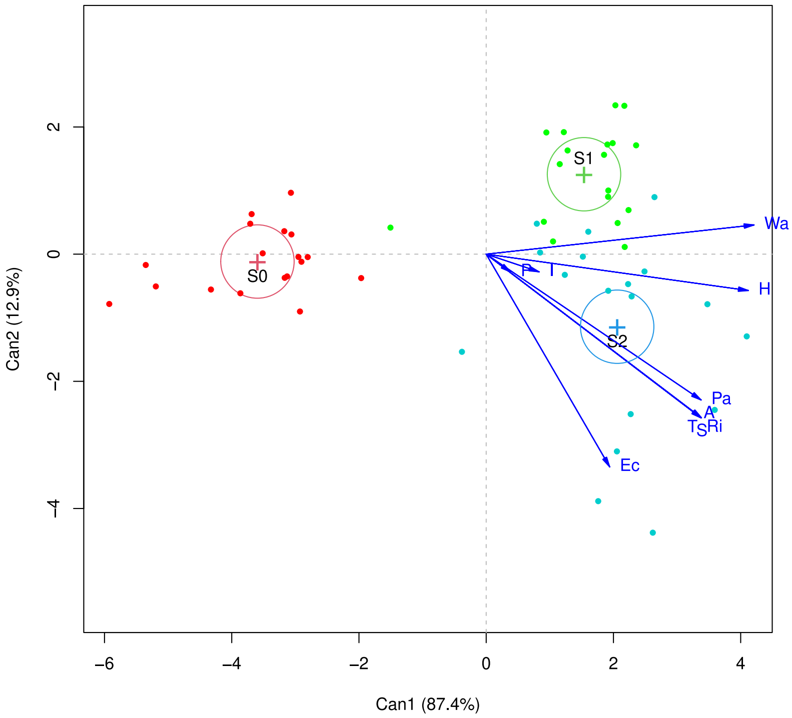

Figure 3. LDA with indication of the confidence circles (for $\alpha = 0.05$) for S_0 (red), S_1 (green), and S_2 (cyan) highlighting the differentiation among scenarios based on the respective SG values (blue arrows). The position of each lot in the space formed by the canonical axes is indicated by dots colored according to the respective scenario. The percentage of the total variance explained by each axis is also reported.

These results are coherent with the expected outcomes of the different urban green planning scenarios and indicate the appropriateness of the proposed SGs to quantify the ecological functions exerted by vegetation. For instance, the increase in the height of the dominant vegetation layer associated with the substitution of several bushes with trees in S_1 and S_2 resulted in higher wind attenuation than in the bush-dominated S_0. Similarly, the use of different types of green materials, such as hedges and trees of various classes, improved biodiversity as expected in both the S_1 and S_2 with respect to S_0. In terms of the spatial arrangement of green materials, S_2 represents a remarkable example of how the ecological connectivity index was actually able to capture the increase in spatial connectivity that was the optimization criterion used in developing S_2 from S_1, which provided, at the same time, significantly higher values of the overall efficiency index. In this context, the acoustic and visual insulations, albeit increasing in S_1 and S_2, were found to be less important than the other parameters in differentiating the scenarios, which is an expected result considering the absence of reference vertical surfaces in public spaces. Similarly, the permeability, which does not directly depend upon urban vegetation, was of limited value in differentiating S_0, S_1, and S_2.

In this context, it is worth noting the colinearity of the photosynthesis, transpiration, shading, and rainfall interception indices, due to their substantially similar equations (which differ with respect to the ϵ and $k_i/kw_i/kd_i$ multipliers; see Table 1). From an ecological perspective, this occurrence is fully justifiable, since the processes are all strictly dependent upon the interception/absorption of light or raindrops by the canopy. In the proposed application, however, the similarity in the information provided by the four indices allows for simplifying, when needed, the set of equations. For example, the assumption of a maximal photosynthetic efficiency, and thus a constant value of ϵ among the lots, may be a common case in urban green planning. In these cases, the photosynthesis and transpiration indices are redundant and can be summarized into a single one. However, ϵ represents a tuning parameter that allows for planners to take into account situations where photosynthesis might by limited by environmental constraints, and, in such cases, the distinction among the indices can be crucial in properly evaluating the expected efficiency of the urban green planning approach. Similar considerations apply to the choice of L_i, k_i, kw_i, and kd_i, the variations of which allow for taking into account the overall plant architecture, phenology, and leaf morphology. A remarkable example is provided by L_i, which can be used to differentiate between deciduous and evergreen plants by either calculating the EI_{green} values for different seasons or by using the yearly average LAI in the SGs, thus including information on plant phenology in calculations.

5. Concluding Remarks

Overall, the proposed methodology bridges the gap between classical urban green planning approaches, thereby ignoring the ecological functions exerted by vegetation and ex post modeling of vegetation roles in determining the dynamics of urban environments. Indeed, the procedure can be viewed as a coarse modeling of vegetation functionality based on simple physical and ecological considerations, which requires far less input data (in terms of quantity and quality) than other modeling approaches (e.g., i-Tree Eco [86]), which makes it usable in ex ante applications. Models such as i-Tree Eco are actually able to provide more accurate estimates of pollution removal, carbon sequestration, plant effects on hydrology, and building energy than our equations, but their complexity requires high quality input data that usually need to be collected in situ, thereby restricting their practical application mostly to ex post analyses. Although the developed indices (SGs) provide only gross estimations of the respective ecological functions, the proposed equations are based on sound assumptions and can be fruitfully applied in comparative approaches to guide the choice (and/or the development) of urban green plans to maximize their ecological efficiency. Moreover, the modularity of the approach, thus allowing for defining custom sets of equations and different weighting values for the different functions exerted by the vegetation, fosters the adaptation of the procedure to a broad spectrum of applications.

The adaptation of the methodology to different contexts can be further promoted by the inherently simple calculations involved, which can be straightforwardly vectorized and automated to provide planners and landscape architects with easy and efficient tools to quickly evaluate the ecological efficiency of their plans. In this context, object-oriented languages such as Java, Python, C++, or R are primary choices, thereby allowing for the representation of each green element as an object with associated parameters, including their spatial coordinates. In turn, such a representation would provide a straightforward means of interfacing the proposed methodology with geographical information systems, thus further promoting its adoption.

As a final remark, it should be noted that the proposed methodology actually splits the planning of urban green planning into two consecutive phases. Indeed, the elements of vegetation can firstly be modeled as simple shapes with specific attributes describing their interaction with the environment, and the attributes can then be used in guiding the choice of the species and the environmental conditions that match the simulated scenarios. On its own, such an approach not only simplifies the overall planning process, but also provides ecological criteria for the selection of the species used in urban plans, thereby promoting the realization of sustainable urban ecosystems.

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