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Evaluation of the Functional Connectivity between the Mangomarca Fog Oasis and the Adjacent Urban Area Using Landscape Graphs

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Abstract: The present research aimed to measure the degree of connectivity and create a map of the ecological connectivity that highlights the real or potential presence of green, ecological, or ecotourism circuits integrating the green infrastructure of San Juan de Lurigancho and the Mangomarca hills using graph theory applications implemented in the Graphab 2.8 software. Mangomarca and Huiracocha Park were selected for this study. In terms of the methodology, a simple approach based on landscape metrics, which are easy to interpret, was proposed to measure the connectivity of the mosaic of patches in the designated area. The IndiFrag software was used to obtain landscape metrics for the structural connectivity analysis. The Graphab software was employed for the functional connectivity analysis. Both tools proved effective in identifying vegetation gaps or the intensity of the greenery. Landsat 8 images from 8 July 2021 and 4 October 2021 were selected for this research due to the lower amount of cloud cover. Concerning the structural connectivity, the TMCl (patch size), NobCl (number of patches), and PerimCl (perimeter) metrics were effective in distinguishing the mosaic of urban landscape patches from the hill landscape. These indices confirm that the urban landscape patches have a higher number of fragments but are smaller in size compared to the hill landscape. Regarding the functional connectivity, it is evident that the patches are connected at lower-cost distances, averaging 7 cost units (210 m) during the wet season and 23 cost units (410 m) during the less humid season. However, these distances are too extensive and do not form ecological corridors. A survey of the population's perception of the maximum separation distances between patches of vegetation cover that could still be considered a green corridor was included. The results indicate that a third of the sample (36%) prefer to walk down a hallway with a maximum separation distance of 10 m, while almost two-thirds (68%) would prefer a maximum separation distance of 50 m. Therefore, city planning should consider actions to reduce these distances and enable ecological connectivity in the area. It is recommended to continue researching the functional connectivity and determining the green corridors in the city to establish monitoring guidelines for the ecological connectivity of the city.

Keywords: Graphab; urban functional connectivity; IndiFrag

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1. Introduction

To live surrounded by gardens and wooded areas in the city can not only be a noble ideal but also constitute a fundamental right of the person, as recognized in numerous legislation, such as the case of Peruvian laws [1] that state we have the right to a balanced and healthy environment [2]. However, cities have been reducing their green spaces, always in tension with other prioritized urban land uses, according to various population interests (which diminish the presence of vegetation).

The theoretical frameworks upon which city planning is based, especially those concerning green areas, have varied from considering a simple conception of parks and gardens to conceptualizing the green or ecological corridor, that is, thinking of urban vegetation as green infrastructure (gardens, parks, wooded areas, fences, orchards, green roofs, etc.), interconnected, and providing ecosystem services [3].

The urgent need for esthetic and cultural ecosystem services, in addition to regulatory and supply services provided by vegetation, has been highlighted in numerous studies. Specifically for the city of Lima [4], it is concluded that "better access to green space in the form of a family garden can significantly improve mental health in an environment of urban marginal neighborhoods".

On the other hand, in the city of Lima, natural ecosystems such as coastal hillsides are also providing recreational and educational ecosystem services to the city. These hillsides have gained importance in social empowerment processes, where it is noted that local communities have self-organized to protect the coastal hillside through ecotourism promotion activities [5].

The urban growth of the city on agricultural lands has led to the reduction of green areas, and consequently, the greenery of the city has been lost [6]. Vegetation in the city is now primarily found in parks and gardens, forming a mosaic of patches of vegetation cover [7]. In some districts, these patches are abundant and almost form integrated coverages, meaning that they are highly connected, forming ecological corridors or networks. The term "green corridor" is used to refer to the ecological corridor in the city, distinguishing it from the ecological corridor in the field for wild populations [8–10].

In other districts, these parks, gardens, or green areas are scattered and dispersed, disconnected, and do not form a green corridor. In this regard, landscape ecology uses landscape metrics to recognize the level of connectivity and fragmentation of the ecological landscape. On this matter, there are numerous works applying the theories and instruments of this discipline to the biology and ecology of conservation in different ecosystems, including urban ecosystems [11–14].

Applying the concept of green corridors, coastal hillsides should be integrated into the city's ecotourism circuits, combining hillsides, archeological sites, and urban recreation sites into a single experience. Currently, people visit a hillside, an archeological site, or a park separately, and there is no integrated option with the enjoyment of a vegetative landscape because there are no green corridors connecting these points of interest [15–17].

For the purpose of implementing such an integrated option with proper planning, it will be advisable to execute a research program with the general goal of developing technical specifications and guidelines for the environmental interpretation trails of hillsides and the design of green corridors connecting urban recreation sites with hillsides.

A paradigmatic case for research is constituted by the Mangomarca hills and the contiguous area in the district of San Juan de Lurigancho due to the presence of a hill, an archaeological area, and the urban area itself. In this context, the present research aimed to measure the degree of connectivity of the green areas (parks and gardens) of the city and the patches of vegetation in the hills in a sector of the district of San Juan de Lurigancho. Connectivity was conceptualized as links, connections, or corridors between parks, gardens, and patches of hill vegetation. Such green corridors would provide routes for walkers who wish to reach the hills via paths with plant presence or vegetation cover. In this case, the vegetation would offer the following ecosystem services: (a) microclimate moderation (increased coolness) and (b) a semi-natural landscape. A scenario was posed of a walk on a sunny summer's day, with varying degrees of need for protection (sunscreen or hat). In this case, green corridors would only have this condition according to the different preferences of walkers regarding the maximum distances between patches of vegetation cover they could walk without solar protection (sunscreen or hat). A survey was conducted to discover the degree of tolerance for such distances (10, 25, 50, 100, 250, and 500 m or more). The survey also inquired about the maximum distance they could tolerate without enjoying a semi-natural landscape. In summary, the connectivity thresholds employed (distances) were not explained by the requirements of some biological species or fauna, nor by any ecological justification. In this case, connectivity was posed within the framework of green corridors of the city, which are spaces of connectivity for people. The concept of ecological corridors was not used within the framework of biological conservation, in which connectivity is a very specific metric for each species. While there may not currently be a significant number of walkers to the hills from the city, it is a scenario that can be encouraged if such green corridors are developed.

To facilitate the delimitation of green areas or vegetation cover of the city and the hills, satellite images were used, specifically the Normalized Difference Vegetation Index (NDVI), which is widely used in vegetation cover studies. The NDVI has been related to various parameters of vegetation dynamics, particularly with those photosynthetic capacity and primary productivity. This index provides a measure of plant greenness intensity and vigor. Sparse vegetation, such as shrubs and grasslands or senescent crops, presents moderate NDVI values (0.2–0.5), while high NDVI values (0.6–0.9) correspond to dense vegetation such as forests or crops in their maximum growth stage. In deserts, the NDVI values are low (0.06–1.2). In the present study, an NDVI threshold equal to or greater than 0.05 was used to delimit vegetation areas or patches of vegetation cover. Two dates of satellite images were used to take into account the seasonality and variability of hill vegetation; that is, the size and density of hill patches are never an absolute value, as they will increase or decrease according to months and years. While in August or September, peak greenness in hills is reached, not all years have the same values. Particularly in El Niño years, the hill greenness intensity values are much higher. The NDVI thresholds of 0.05 were established for two dates (8 July 2021 and 4 October 2021) and for two scenarios (urban area and hill). The dates only indicate the availability of cloud-free images for those moments; on the other hand, the binarization of the images at NDVI 0.05 was only a device to obtain a map of the green areas of the city and the hills (i.e., equal to or greater than NDVI 0.05 implies vegetation cover; less than NDVI 0.05 equates to areas without vegetation).

A structural connectivity analysis of the green areas (parks and gardens) was incorporated, which was carried out with IndiFrag software. This analysis explains how large or small the patches of green areas are, and if their distribution is regular or aggregated. If the distribution is more aggregated, it is more feasible for them to form a corridor; although if aggregation only occurs in one sector, it will result in disconnected zones.

To calculate the distance between vegetation patches, a graph structure was used, using Graphab 2.8 software. This graph structure consists of nodes and links that connect them. In this case, the nodes are the green areas (parks and gardens) of the city and the patches of hill vegetation. The mentioned program allows for obtaining the links or connections between the patches of vegetation cover according to a graph structure. Such links can be modeled or estimated as a Euclidean distance or a cost surface. The term "cost" in ecological connectivity analysis equates to environmental resistance or some factor of the environment that reduces the connectivity or the possibility of species individuals passing from one vegetation patch to another. Such ecological criteria were only referential because in the present research such a cost or resistance was associated with the preference of a person regarding the green areas of the city and the hill ecosystem. In this case, the factor of the environment that reduces the connectivity between green areas would be the high summer temperature. That is, as the temperature is higher and the distance between green areas is greater, there will be more resistance (cost) to walking under the sun.

Determining costs requires expert judgment and can be arbitrary. In contrast, distance (m) is an indicator that is easier to understand for connectivity. In this research, the Euclidean distances and costs were calculated. The cost values used could constitute theorized data to form a comparative basis based on estimating their correlation or relationship with other variables, starting with the Euclidean distance (m).

A practical result of this research will be the elaboration of maps of the ecological connectivity of green areas (parks and gardens and hill patches) that show the real or potential presence of green, ecological, or ecotouristic circuits integrating the green infrastructure of San Juan de Lurigancho and the Mangomarca hills based on the applications of graph theory implemented in Graphab software. In this case, Mangomarca and Huiracocha Park were selected. Another practical result will be the adjustment of a methodology to estimate the level of connectivity of the different patches of green areas of the city and the hills.

Urban areas pose challenges for implementing ecological networks. Research was conducted on the feasibility of planning an ecological network in an urban landscape, such as the urban area of Phoenix [18]. They previously developed and articulated an ecological network plan, for which they conducted three main analyses: (1) patch content analysis, (2) corridor content analysis, and (3) network structure analysis. With the first two analyses, they examined the internal characteristics and immediate context of each of the 89 elements of the ecological network. In the network structure analysis, they incorporated patch and corridor analyses, as well as indicators describing the interrelationships between landscape elements. In each of these analyses, they compared the existing condition with an optimal plan to demonstrate the expected level of change, concluding that an ecological network plan provides a modest but significant improvement in the ecological systems for the urban area of Phoenix [18].

Similarly, ecological corridors are effective in preventing ecosystem degradation and biodiversity loss by promoting connectivity between discrete habitat patches [19]. Therefore, the identification of these corridors is crucial for biodiversity conservation and landscape planning. For the city of Beijing, a new approach was proposed, integrating continuous spatial wavelet transform and kernel density estimation to objectively identify the ecological corridor width thresholds in this megacity. The InVEST model was applied to extract the central habitat patches and build ecological resistance surfaces based on natural conditions and human activities [19].

An urban ecological network, as an organic structure integrating green spaces, can effectively reduce the ecological risks and protect the biodiversity if landscape connectivity is maintained [20]. Applying ecological network modeling techniques (Graphab) and scenario simulation (FLUS model) for the Chaoyang district, Beijing, they assessed the environmental impact of different development scenarios on the landscape connectivity indices. Their results show that the probability of connectivity (PC) is highly positive (102.1%) under the Master Plan scenario compared to urban expansion, which decreases by 59.7%. Overall, this study proposes a framework for decision-makers to resolve planning conflicts between urban expansion and biodiversity conservation, especially for transitioning cities [20].

The urban ecological network has gained substantial interest in the context of sustainable urban development research in recent years [21–29]. It guides the optimization of urban ecological spatial design, which is an important means of inventory development and ecological construction [30]. However, traditional urban construction methods may not be suitable for complex environments, potentially leading to the inaccurate extraction of urban ecological networks. This study aimed to enhance understanding of the current distribution and composition of key elements in urban ecological networks. In this study, an optimized evaluation method involving ecological source patches and resistance surfaces was obtained to identify and extract an urban ecological network [31].

The need to conserve and create links between fragmented habitats has led to various techniques for maximizing connectivity. The most popular method used to assess habitat linkage design is the Least Cost Path (LCP) analysis, which designates a landscape resistance surface based on the hypothetical "costs" imposed by landscape components on species movement and identifies routes that minimize the cumulative costs between locations. While LCP analysis is a valuable method for conservation planning, its current application has several weaknesses, with three common ones standing out. First, LCP models often rely on remote-sensing habitat maps, but few studies evaluate whether such maps are adequate indicators of factors affecting animal movement or consider the effects of adjacent habitats. Second, many studies use expert opinions to assign costs associated with landscape features, but few validate these costs with empirical data or assess the model's sensitivity to errors in cost allocation. Third, studies considering multiple alternative movement routes often propose width or length requirements for links without justification.

A graph represents a landscape as a set of nodes (e.g., habitat patches) connected to some extent by edges that functionally link pairs of nodes (e.g., through dispersal). Graph theory is well-developed in other fields, including geography (transportation networks, routing applications, location problems) and computer science (network and circuit optimization). Graph theory can be applied to connectivity problems in heterogeneous landscapes based on a hypothetical landscape mosaic of habitat patches in a non-habitat matrix. The results suggest that a simple graph construction can serve as a guide for decision-making regarding the relative importance of individual patches for the overall landscape connectivity.

Graphab is a software application for modeling habitat networks. It has been used in many studies, initially in ecological studies to analyze the role of landscape connectivity in field-measured biological responses, and secondly, to support decisions related to biodiversity conservation. One of the most popular approaches is a theoretical graph method promoted in ecology, known as habitat networks or landscape graphs. In these graphs, nodes are the set of habitat patches occupied by a particular species, and links are potential connections between them, weighted by the distances or probabilities of dispersal. These graphs provide users with a basis for visualizing ecological networks and characterizing their functional properties through connectivity metrics. On a larger scale of urban planning, Graphab has been used to include ecological connectivity in the assessment of urban development impact. Most of these planning approaches were based on spatial simulations of urban development scenarios, either to compare potential impacts of various urban forms or to plan actions to mitigate urban expansion [31]. Other urban-planning studies have used Graphab to assess the biological potential of green spaces or evaluate their permeability as steppingstones [32].

IndiFrag is a processing tool used for extracting a set of indices and variables that quantitatively describe the level of fragmentation and spatial distribution of land uses in response to the morphological, spatial, and typological properties of cartographic objects [33].

A decision tree algorithm was proposed that allows the detection of connectivity and fragmentation processes based on three parameters that must be determined before and after landscape transformation: area, perimeter length, and number of patches of the focal landscape class [34].

2. Materials and Methods

2.1. Determination of the Study Area and Methodological Design

Figure 1 shows the study area, which includes the Mangomarca hillside and the adjacent urban sector toward Huiracocha Park.

Figure 2 shows a flow chart of the methodological process that guided the research. In this figure, the literal "a" represents a satellite image; the literal "b", an NDVI image; and the literal "c", a binary NDVI image. The literal "d" shows an example of the map of green corridors in the study area.

2.2. Obtaining NDVI from Satellite Images

The analysis was conducted based on freely available Landsat 8 (LC08) or Landsat 9 (LC09) images, as obtained from the geoserver https://earthexplorer.usgs.gov/ (accessed on 8 June 2021) with path row 007068. While both the LC08 and LC09 images have a spatial resolution of 30 m (medium resolution), the working level was at the systematic reconnaissance level.

Images that were free of clouds or had minimal cloud coverage (less than 10% of the study area) were downloaded. The NDVI was obtained for all the selected images. In the case of images with clouds, the cloud and shadow boundaries were delineated to control the NDVI data that could be influenced by clouds. Cloud and shadow polygons and masks were obtained using standard methodology through ArcGIS. Two cloud-free images were selected for the study area, LC08-L2SP-007068-20181004, corresponding to the dates 4 October 2018 (end of the wet season) and 8 July 2021 (beginning of the wet season).

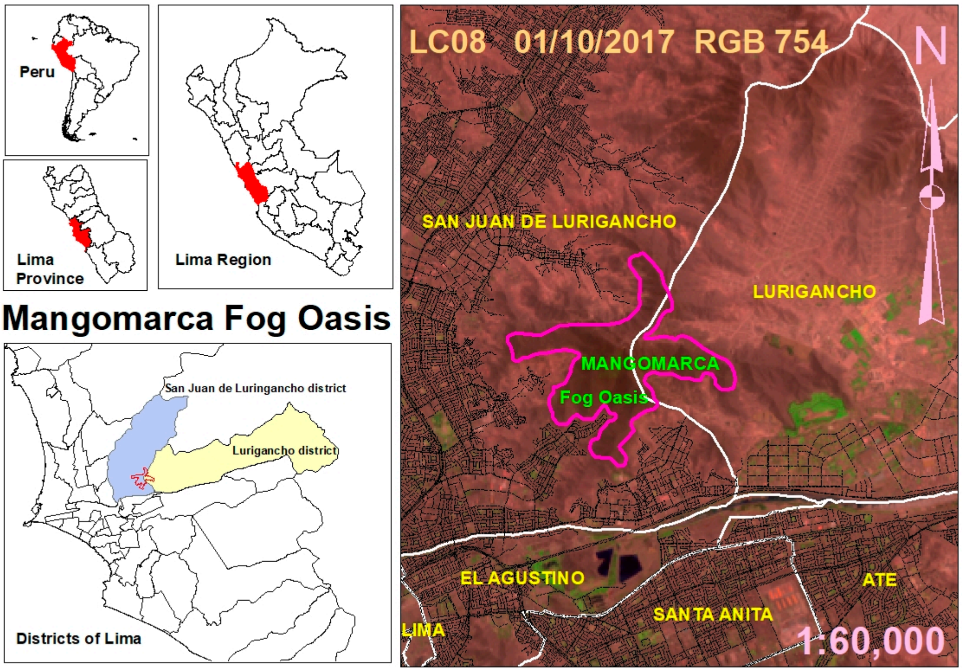

Figure 1. Location of the study area.

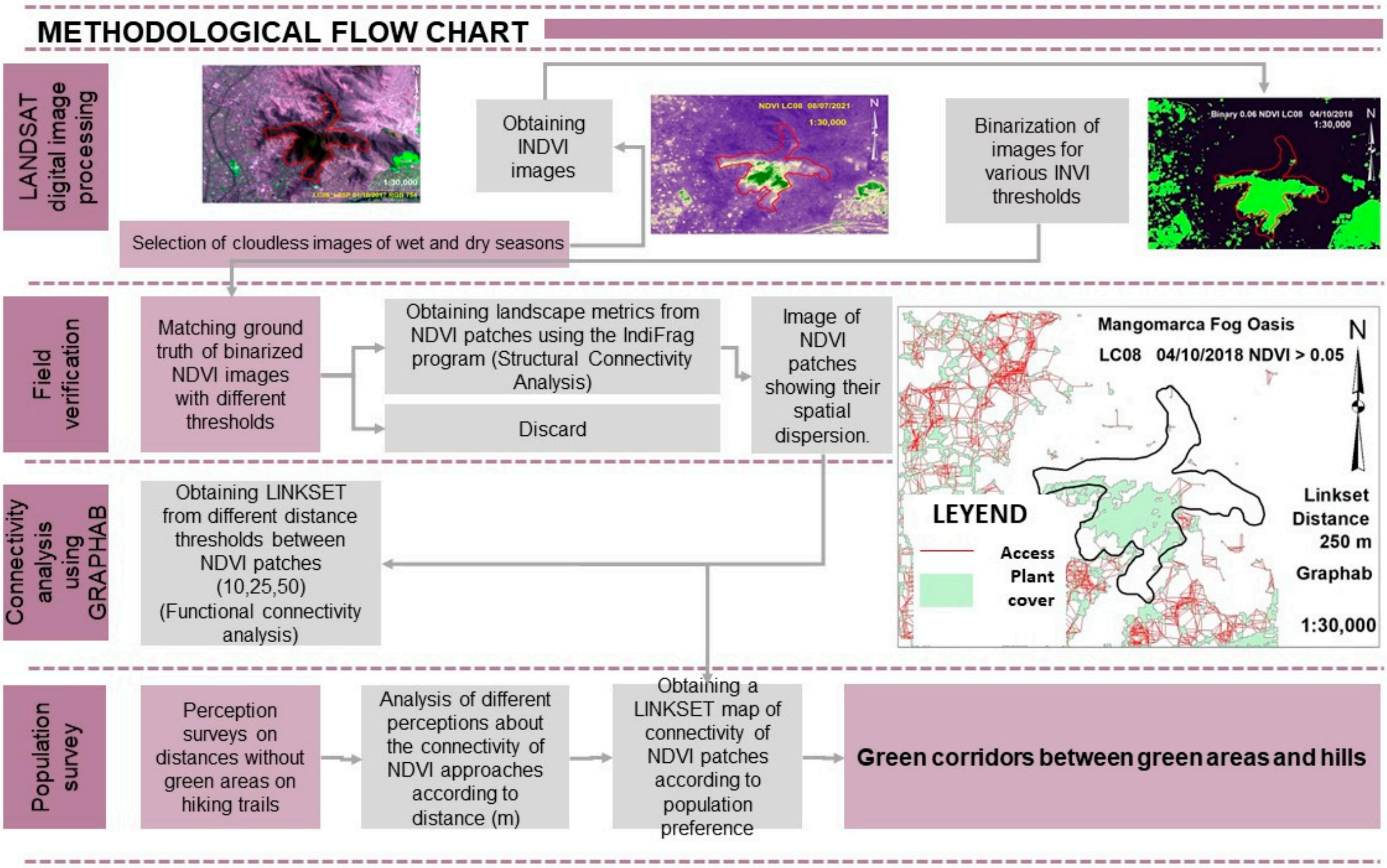

Figure 2. Flowchart of the methodological procedure.

To obtain the vegetation cover patches, the NDVI images were binarized using the thresholds of 0.05, 0.08, 0.1, 0.15, and 0.2. All the mentioned images were clipped following the boundaries of the rectangle corresponding to the delimited study area, which included the Mangomarca hillside and Huiracocha Park.

For each NDVI image and each threshold, the initial mosaic of vegetation cover patches was converted from raster to polygons to obtain the area and perimeter of each patch.

2.3. Structural Connectivity Assessment

A structural connectivity analysis of the vegetation cover patches was conducted for the images dated 4 October 2018 and 8 July 2021. The software program IndiFrag was used.

At the patch or object level, the area (AreaO), perimeter (PerimO), and the perimeter–area ratio (RPA) were considered, resulting in a list of all the patches (for all the binary images with the established thresholds). At the class level (entire vegetation cover), the same metrics were obtained but averaged for the entire class (vegetation cover): AreaO, PerimO, RPA, and NobCl (number of objects or patches for the class). Additionally, slightly more complex metrics than those previously mentioned were obtained, such as:

2.3.1. Average Object Size (TM)

It is equal to the average size of objects within a class or superobject (m^2).

2.3.2. Boundary Dimension (dimB)

It represents the relationship between the object's area and perimeter, measuring the complexity and randomness of the classes. It is obtained at the class level, generally for the entire study area, excluding superobjects.

2.3.3. Mean Euclidean Distance of the Nearest Neighbor (DEM)

It quantifies the isolation of objects within each class. It is equal to the average distance between the nearest objects of the same class in a superobject (m). This metric is obtained for the class.

2.3.4. Frog Jump (LPF)

The relationship between the area of jumps or isolated objects of a class located separately at a distance from the rest of the class and the area of the entire class (%). It is obtained at the class level.

2.3.5. Mean Perimeter–Area Ratio (RMPA)

The relationship between the object's area and perimeter, describing how the perimeter of an object increases per unit increase in the object's area. It is obtained at the object level (RPA), class level (RMPACL), and superobject level (RMPASO).

2.3.6. Evaluation of Functional Connectivity

To assess the functional connectivity, the software program Graphab was utilized. This choice was based on the background of the study 'Evaluation of green infrastructure and ecological connectivity in the canton of Curridabat', which employs Graphab to evaluate infrastructure connectivity in that city. In this study, the connectivity probability was defined as the likelihood that two randomly selected individuals of the same species in the study area would come into contact. In Annex 2. Parameters used in Graphab, the following was indicated: Minimum patch size: 0.01 ha, units forests, forest-riparian forest, tiles; maximum dispersal distance 22.9 m, 22.15 m, 22.18 m, 24.18 m. Probability of movement 0.05; the type of distance was dispersal capability, cost impedance, cost scale 1, 10, 1000, 10,000, planar topology. [35]

The premise was to evaluate the impedances through the cost. In the Graphab software, an 'edge' is the line that connects one node (patch centroid) to another node, whose length range is determined by the threshold set by the maximum distance in cost units assigned to the analysis; on the other hand, the 'Linkset' connects patch edges not in the same direction as the 'edge' line. Regarding the 'Linkset', the difference between 'planar' and 'complete' must be taken into account. The three parameters required by the program were determined: type of distance, maximum distance, and landscape categories. The 'habitat patch codes' were marked in blue. A minimum area size of 0.05 ha was considered. This minimum patch area is the minimum area in hectares required for a habitat patch to become a graphical node.

3. Results

3.1. Regarding the Maximum Distances between Green Areas or Connectivity Thresholds

The conducted survey was built on the premise that the calculated distances correspond to the connection or separation of patches of green areas. The more connected or separated patches of vegetation cover are, the more they qualify as a green corridor. For example, for individuals who cannot tolerate a walk beyond 50 m in full sun, if the patches of green areas in the area exceed that threshold, those individuals would perceive such green areas as disconnected. In that case, the green areas would not constitute a green corridor. The survey conducted with a population of students yielded the following results.

The table shows that one-third of the sample (36%) prefer a walk in a corridor with a maximum separation of 10 m, and almost two-thirds (68%) would prefer a maximum distance of separation of 50 m. Table 1 illustrates, in terms of the cost (environmental resistance) or distance (meters), the sectors of the study area that are shown to be connected for the distance thresholds.

Table 1. Preference for distances between patches of green areas on a sunny day's walk.

Prompt	**Response**	
What distance could you comfortably walk without sun protection (neither sunscreen nor hat)?	Frequency (person)	"Relative frequency (%)"
(a) Approximately 10 m without sun protection.	16	36
(b) Approximately 25 m without sun protection.	7	16
(c) Approximately 50 m without sun protection.	7	16
(d) Approximately 100 m without sun protection.	6	14
(e) Approximately 250 m without sun protection.	3	7
(f) Approximately 500 m or more without sun protection.	5	11
TOTAL	44	100

3.2. In Relation to Structural Connectivity

The analysis of the structural connectivity was conducted using the IndiFrag software. Figure 3 shows that the metrics TMCl (patch size), NobCl (number of patches), and PerimCL (patch perimeter) cluster differently compared to the other similarly grouped metrics (DimB, LPF, RMPACl, AreaCl, DEM, COHESI). For the purpose of a structural connectivity analysis, these metrics (TMCl, NobCl, and PerimCL) are crucial as they provide information indicating that they are not correlated. From the group of samples that overlap in Figure 3, it is evident that they are highly correlated, but it would be advisable to consider COHECl to some extent, as this metric remains somewhat less correlated with the other overlapping metrics in Figure 3.

The above-mentioned findings align with the work, which establishes an algorithm to determine the situation in which a landscape would be fragmented, based on the patch size, number of patches, and perimeter–area ratio (Tables 1–4).

In relation to the characteristics of the mosaic of vegetation cover patches, the green landscape is different in urban conditions and in hilly conditions. Between the thresholds of NDVI 0.05 and NDIV 0.1, the differences are not as clear-cut as in the case between cities and hills (as evidenced in Figure 3 showing the PCA main components analysis), but there are differences as shown in Figure 4 in the multidimensional scaling (MDS) analysis. The above is evident, given that the green areas in a city respond to the criterion of gardens, parks, trees, fences; however, in the hills the intensity of the greenery responds to the condition of shrubby bushes and grasslands.

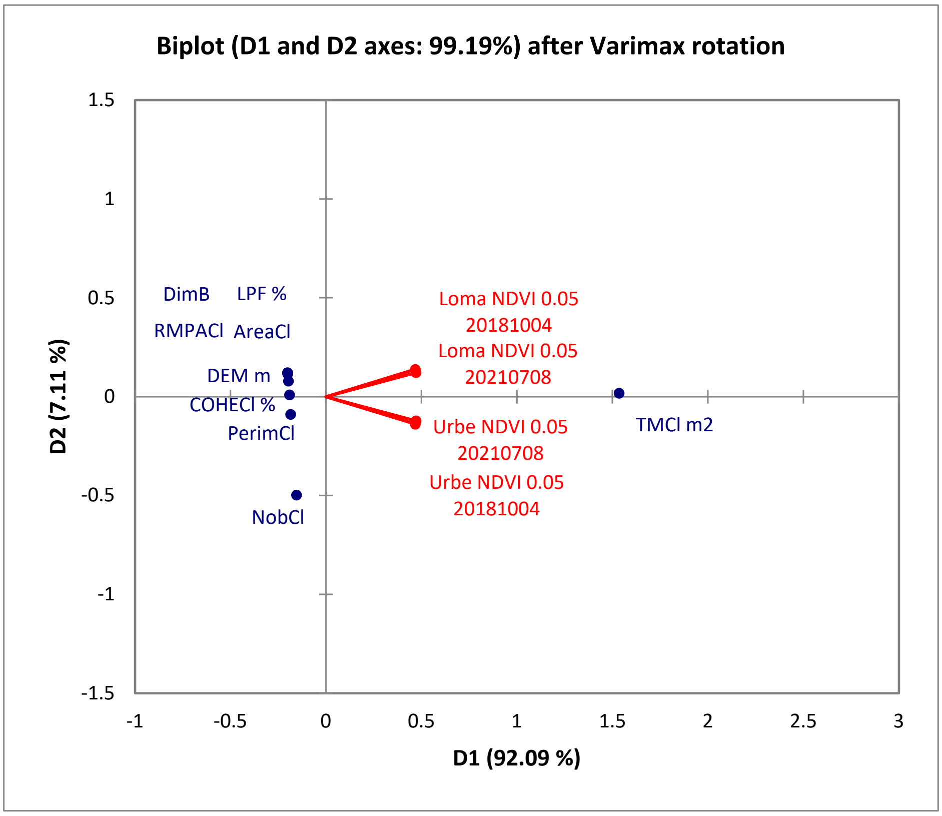

Figure 3. PCA of the landscape metrics by the NDVI threshold and image date.

Table 2. Preference for distances between patches of green areas on a sunny day's walk.

Prompt	Response	
Regarding your preference regarding the landscape on a city walk, could you indicate what maximum distance you could tolerate for a walk without the presence of vegetation or gardens, fences, shrubs, trees, groves?	Frequency (person)	"Relative frequency (%)"
(a) Approximately 10 m without vegetation presence.	16	36
(b) Approximately 25 m without vegetation presence.	9	20
(c) Approximately 50 m without vegetation presence.	7	16
(d) Approximately 100 m without vegetation presence.	4	9
(e) Approximately 250 m without vegetation presence.	2	5
(f) Approximately 500 m or more without vegetation presence.	6	14
TOTAL	44	100

Table 3. Landscape metrics for vegetation cover patches of hills and urban areas, Values obtained through IndiFrag. AreaCl: class area; PerimCl: average class perimeter; NobCl: number of patches per class; LPF: frog jump; TMCl: average patch size per class; DimB: boundary dimension; RMPACl: mean perimeter-area ratio; DEM: mean Euclidean distance of the nearest neighbor, COHECl: cohesion per class.

Metrics	Hill NDVI 0.05 20210708	Urban NDVI 0.05 20210708	Hill NDVI 0.05 20181004	Urban NDVI 0.05 20181004
AreaCl	3.25	4.76	1.42	4.23
PerimCl	19.25	138.12	18.14	190.57
NobCl	13	360	21	579
LPF %	0.001	0.13	0.01	0.15
TMCl m^2	250,200	13,209.3	67,485	7301.29
DimB	1.11	1.11	1.09	1.09

Table 3. *Cont.*

Metrics	Hill NDVI 0.05 20210708	Urban NDVI 0.05 20210708	Hill NDVI 0.05 20181004	Urban NDVI 0.05 20181004
RMPACl	0.18	0.14	0.73	0.14
DEM m	39.82	44.4	69.89	37.14
COHECl %	99.98	99.7	99.92	99.32

Table 4. Size of the vegetation cover patches in hills and urban areas.

NDVI Date Number of patches	0.1 8 July 2021 13	0.1 8 October 2018 21	0.05 8 July 2021 360	0.05 8 October 2018 579
Statisticians	Hill patch area		Urban patch area	
Minimum m	43.96	0.787	6.91	8.643
Maximum m	3,218,650.00	1,263,470.000	1,452,320.00	339,608.000
Median m	616.19	1214.870	1228.86	1228.860
Mean m	250,199.79	67,485.021	13,209.33	7301.293
Variation coefficient (n − 1)	3.56	4.075	6.37	2.881
Mean absolute deviation m	456,684.65	117,718.282	19,295.87	8842.862
Median absolute deviation	572.23	598.679	612.67	612.669
Fashion m	616.19	616.191	616.19	616.191
Frequency fashion	5	6	83	142

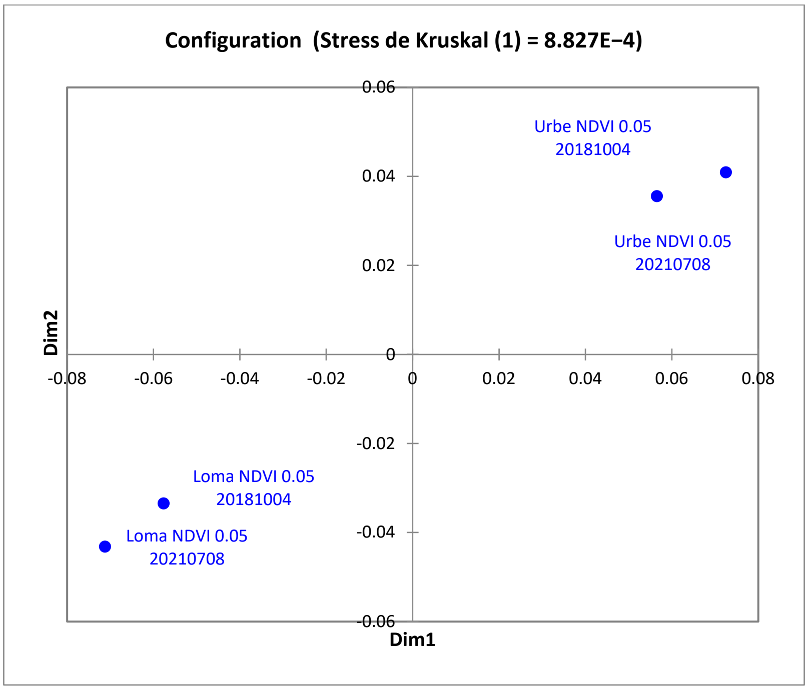

Figure 4. MDS of the landscape metrics by the NDVI threshold and image date.

3.3. Regarding Functional Connectivity

The analysis of the functional connectivity was conducted using Graphab software. The study area rectangle for the LC08 image of 4 October 2021 only displayed a mosaic of vegetation cover patches for values 0.05, 0.08, and 0.1, including the hill vegetation cover. From the NDVI threshold of 0.1 onwards, the intensity of the hill greenery disappeared. For the month of October, the hill vegetation cover lost its NDVI intensity as seasonal plants dried up (remaining as seeds or geophytes in the dry period of the hill).

Table 5 summarizes the information presented in Tables 6–11, showing the mean Euclidean distance (m) for the different costs or resistances, for comparative purposes, for the four situations: patch mosaic for NDVI 0.05 and NDVI 0.1 greenness intensities, respectively, for the months of July (higher humidity) and October (less humid). (Figure 5).

Table 5. Perimeter of vegetation cover patches in hills and urban areas.

NDVI	0.1	0.1	0.05	0.05
Date	8 July 2021	8 October 2018	8 July 2021	8 October 2018
Number of patches	13	21	360	579
Statistics	Hill patch area		Urban patch area	
Minimum m	32.298	9.524	21.45	8.643
Maximum m	16,924.500	12,666.600	16,394.50	339,608.000
Median m	113.186	169.765	170.21	1228.860
Mean m	1480.552	863.903	383.67	7301.293
Variation coefficient (n − 1)	3.136	3.164	2.75	2.881
Mean absolute deviation m	2375.992	1221.878	343.72	8842.862
Median absolute deviation	67.045	56.579	57.03	612.669
Fashion m	113.186	113.186	113.19	616.191
Frequency fashion	5	6	128	142

Table 6. Surface perimeter relationship of vegetation cover patches of hills and cities.

NDVI	0.1	0.1	0.05	0.05
Date	8 July 2021	4 October 2018	8 July 2021	4 October 2018
Number of patches	13	21	360	579
Statistics	RPA hill patch	RPA hill patch	RPA urban patch	RPA urban patch
Minimum m	0.01	0.010	0.011	0.011
Maximum m	0.73	12.109	3.105	1.953
Median m	0.18	0.140	0.138	0.138
Mean m	0.18	0.731	0.145	0.138
Variation coefficient (n − 1)	1.00	3.568	1.328	1.117
Mean absolute deviation m	0.09	1.084	0.072	0.069
Median absolute deviation	0.05	0.044	0.046	0.046
Fashion m	0.18	0.183687	0.183687	0.183687
Frequency fashion	5	6	83	142

Table 7. Distance between patches according to the cost for the NDVI 0.05 image on 4 October 2021.

Cost	No. of Links	Minimum Distance (m)	Maximum Distance (m)	Median Dist (m)	Mean Dist (m)	Variation Coefficient (n − 1)	Lower Limit of the Mean (95%)	Upper Limit of the Mean (95%)	Mean Absolute Deviation	Median Absolute Deviation
1										
2	22	42	60	42.43	47.22	0.17	43.67	50.77	6.97	0.00
3	54	42	90	72.43	67.75	0.28	62.64	72.87	16.73	12.43
4	68	42	120	84.85	77.17	0.33	71.07	83.28	20.92	17.57
5	103	42	150	90.00	98.83	0.37	91.62	106.05	32.59	30.00
6	151	42	180	132.43	120.61	0.37	113.47	127.76	39.13	37.28
7	196	42	210	150.00	138.47	0.37	131.28	145.67	43.61	37.28
8	243	42	240	162.43	155.58	0.37	148.27	162.88	48.11	42.43
9	300	42	270	180.00	174.73	0.37	167.29	182.17	54.73	49.71
10	356	42	300	199.71	192.15	0.38	184.59	199.71	60.93	54.85
11	429	42	330	222.43	213.50	0.38	205.79	221.21	68.59	62.13
12	480	42	360	240.00	227.70	0.38	219.87	235.52	73.74	67.28
13	549	42	390	259.71	246.32	0.39	238.33	254.31	80.47	72.43
14	611	42	420	272.13	262.59	0.39	254.45	270.74	86.58	82.72
15	684	42	450	294.85	281.17	0.39	272.85	289.49	93.67	90.00
20	1069	42	600	386.98	370.65	0.41	361.60	379.70	128.62	123.02
21	1148	42	630	403.49	387.56	0.41	378.39	396.72	135.12	131.36
22	1205	42	660	416.98	399.89	0.41	390.61	409.16	140.04	132.43
23	1302	42	690	439.71	420.42	0.41	410.97	429.86	148.12	137.57
24	1401	42	720	457.28	440.70	0.42	431.12	450.29	155.99	146.98
25	1487	42	750	476.98	457.79	0.42	448.10	467.48	162.59	152.13
30	1946	42	900	566.98	544.23	0.42	534.05	554.40	195.17	185.15
35	2374	42	1050	653.97	622.67	0.43	611.93	633.41	227.44	212.13
40	2805	42	1200	721.25	699.61	0.44	688.31	710.92	259.26	250.29
45	3297	42	1350	801.84	785.73	0.44	773.81	797.65	297.04	282.43
50	3759	42	1500	874.26	864.73	0.45	852.28	877.19	332.75	326.98

Table 8. Distance between patches according to the cost for the NDVI 0.1 image from 7 August 2021.

Cost	No. of Links	Minimum Distance (m)	Maximum Distance (m)	Median Dist (m)	Mean Dist (m)	Variation Coefficient (n − 1)	Lower limit of the Mean (95%)	Upper limit of the Mean (95%)	Mean Absolute Deviation	Median Absolute Deviation
1										
2	27	42	60	42.43	48.28	0.17	44.94	51.62	7.81	0.00
3	37	42	90	60.00	56.57	0.29	51.19	61.95	13.76	17.57
4	50	42	120	60.00	70.34	0.39	62.53	78.14	23.82	17.57
5	56	42	150	72.43	77.75	0.44	68.68	86.81	29.55	30.00
6	72	42	180	90.00	98.50	0.50	86.92	110.09	43.10	47.57
7	97	42	210	114.85	124.44	0.49	112.07	136.82	55.78	60.00
8	124	42	240	166.07	146.42	0.47	134.21	158.62	62.14	51.21
9	150	42	270	189.85	165.71	0.46	153.53	177.89	66.01	57.43
10	170	42	300	199.71	180.08	0.45	167.79	192.37	69.10	60.00
11	199	42	330	212.13	199.70	0.45	187.27	212.13	74.04	67.28
12	233	42	360	234.85	221.33	0.44	208.74	233.91	81.31	72.43
13	259	42	390	247.28	236.95	0.44	224.26	249.64	86.78	77.57
14	296	42	420	270.00	258.35	0.43	245.49	271.21	94.58	84.85
15	339	42	450	300.00	281.03	0.43	268.12	293.93	102.21	95.15
20	564	42	600	414.85	378.88	0.41	366.08	391.68	130.55	112.72
21	597	42	630	424.26	391.99	0.41	379.13	404.84	134.52	116.98
22	624	42	659	432.43	402.94	0.41	389.99	415.89	138.03	120.00
23	663	42	690	446.98	419.13	0.41	405.98	432.27	143.57	127.28
24	704	42	720	460.92	435.90	0.41	422.55	449.25	149.72	130.92
25	749	42	750	474.85	453.93	0.42	440.38	467.48	156.53	137.57
30	948	42	900	539.12	531.83	0.43	517.37	546.29	189.57	180.00
35	1133	42	1050	604.26	604.62	0.44	589.14	620.11	224.76	206.98
40	1308	42	1200	689.12	674.36	0.45	657.83	690.90	259.13	242.13
45	1494	42	1350	749.12	748.90	0.46	731.28	766.53	295.77	284.56
50	1494	42	1350	799.706	808.540	0.47	789.98	827.10	326.93	314.56

Table 9. Distance between patches according to the cost for the NDVI 0.05 image from 4 October 2021.

Cost	No. of Links	Minimum Distance (m)	Maximum Distance (m)	Median Dist (m)	Mean Dist (m)	Variation Coefficient (n − 1)	Lower Limit of the Mean (95%)	Upper Limit of the Mean (95%)	Mean Absolute Deviation	Median Absolute Deviation
1										
2	295	42	60	42.43	49.34	0.17	48.35	50.32	8.39	0.00
3	564	42	90	60.00	64.29	0.28	62.83	65.75	15.64	17.57
4	770	42	120	72.43	77.23	0.34	75.36	79.10	22.90	23.79
5	999	42	150	90.00	91.44	0.38	89.25	93.62	30.65	30.00
6	1282	42	180	114.85	108.46	0.41	106.00	110.91	39.47	42.43
7	1592	42	210	127.28	126.01	0.43	123.36	128.66	47.19	47.57
8	1909	42	240	150.00	142.77	0.43	139.99	145.56	54.29	54.85
9	2260	42	270	169.71	160.35	0.44	157.45	163.25	61.13	60.00
10	2667	42	300	187.28	179.74	0.44	176.72	182.75	68.54	67.28
11	3033	42	330	204.85	196.42	0.44	193.32	199.51	74.90	72.43
12	3409	42	360	222.43	213.06	0.44	209.88	216.24	81.33	77.57
13	3871	42	390	242.13	232.59	0.45	229.33	235.85	88.90	84.85
14	4317	42	420	264.85	250.61	0.45	247.28	253.94	95.70	92.13
15	4775	42	450	282.43	268.40	0.44	265.01	271.78	102.32	97.28
20	7623	42	600	386.98	365.60	0.44	362.02	369.18	136.47	127.28
21	8241	42	630	409.71	384.52	0.44	380.91	388.13	142.81	132.43
22	8849	42	660	427.28	402.52	0.43	398.88	406.16	148.86	139.71
23	9524	42	690	450.00	421.93	0.43	418.27	425.59	155.31	144.85
24	10141	42	720	466.69	439.25	0.43	435.57	442.94	161.13	150.00
25	10782	42	750	484.26	456.90	0.43	453.19	460.61	167.04	154.26
30	14363	42	900	581.54	549.20	0.43	545.36	553.04	198.85	183.02
35	18336	42	1050	674.56	641.76	0.43	637.81	645.72	231.35	215.15
40	22543	42	1200	771.84	732.28	0.42	728.22	736.34	263.76	246.40
45	26957	42	1350	866.98	821.46	0.42	817.29	825.63	295.96	275.15
50	31546	42	1500	953.97	909.33	0.43	905.06	913.60	328.00	308.16

Table 10. Distance between patches according to the cost for the NDVI 0.05 image from 7 August 2021.

Cost	No. of Links	Minimum Distance (m)	Maximum Distance (m)	Median Dist (m)	Mean Dist (m)	Variation Coefficient (n − 1)	Lower Limit of the Mean (95%)	Upper Limit of the Mean (95%)	Mean Absolute Deviation	Median Absolute Deviation
1										
2	163	42	60	42.43	50.51	0.17	49.15	51.87	8.73	0.00
3	296	42	90	60.00	64.25	0.27	62.27	66.24	15.13	17.57
4	418	42	120	72.43	78.27	0.34	75.72	80.83	23.22	30.00
5	550	42	150	90.00	93.11	0.38	90.15	96.08	31.07	30.00
6	707	42	180	114.85	109.94	0.41	106.65	113.23	39.06	42.43
7	842	42	210	127.28	124.24	0.42	120.69	127.78	45.64	42.43
8	987	42	240	144.85	139.30	0.44	135.51	143.09	52.72	54.85
9	1153	42	270	157.28	156.08	0.45	152.06	160.09	60.07	60.00

Table 10. *Cont.*

Cost	No. of Links	Minimum Distance (m)	Maximum Distance (m)	Median Dist (m)	Mean Dist (m)	Variation Coefficient (n − 1)	Lower Limit of the Mean (95%)	Upper Limit of the Mean (95%)	Mean Absolute Deviation	Median Absolute Deviation
10	1341	42	300	174.85	174.39	0.45	170.16	178.61	68.27	67.28
11	1508	42	330	192.43	190.24	0.46	185.84	194.63	75.41	77.57
12	1687	42	360	212.13	206.91	0.46	202.35	211.46	82.65	82.72
13	1907	42	390	234.85	226.49	0.46	221.77	231.20	90.95	90.00
14	2110	42	420	252.43	243.88	0.46	239.05	248.71	97.88	97.28
15	2297	42	450	270.00	259.53	0.46	254.60	264.47	104.21	102.43
20	3584	42	600	374.56	356.73	0.46	351.36	362.10	141.08	135.44
21	3854	42	630	392.13	374.96	0.46	369.54	380.37	147.46	144.85
22	4130	42	660	414.85	393.07	0.46	387.61	398.53	153.85	144.85
23	4420	42	690	439.71	411.64	0.45	406.14	417.14	160.34	150.00
24	4741	42	720	459.41	431.58	0.45	426.03	437.12	167.22	157.28
25	5029	42	750	480.00	449.02	0.45	443.44	454.60	173.10	160.29
30	6595	42	900	570.00	538.47	0.44	532.69	544.25	203.30	189.41
35	8285	42	1050	662.13	628.02	0.44	622.03	634.00	235.45	219.41
40	10106	42	1200	752.13	718.21	0.44	712.03	724.40	268.95	251.98
45	12007	42	1350	844.26	806.49	0.44	800.13	812.85	302.19	284.56
50	14068	42	1500	941.54	897.37	0.44	890.84	903.91	336.51	316.69

Table 11. Average maximum distances per resistance surface for the connectivity of vegetation cover patches in hills and cities.

Cost	Minimum	Maximum	Mean NDVI 0.1 4 October 2021	Mean NDVI 0.1 8 July 2021	Mean NDVI 0.05 4 October 2021	Mean NDVI 0.05 8 July 2021
1	0	0	0	0	0	0
2	42	60	47.22	48.28	49.34	50.51
3	42	90	67.75	56.57	64.29	64.25
4	42	120	77.17	70.34	77.23	78.27
5	42	150	98.83	77.75	91.44	93.11
6	42	180	120.61	98.50	108.46	109.94
7	42	210	138.47	124.44	126.01	124.24
8	42	240	155.58	146.42	142.77	139.30
9	42	270	174.73	165.71	160.35	156.08
10	42	300	192.15	180.08	179.74	174.39
11	42	330	213.50	199.70	196.42	190.24
12	42	360	227.70	221.33	213.06	206.91
13	42	390	246.32	236.95	232.59	226.49
14	42	420	262.59	258.35	250.61	243.88
15	42	450	281.17	281.03	268.40	259.53
20	42	600	370.65	378.88	365.60	356.73
21	42	630	387.56	391.99	384.519	374.955
22	42	660	399.89	402.94	402.521	393.074
23	42	690	420.42	419.13	421.930	411.640
24	42	720	440.70	435.90	439.254	431.577
25	42	750	457.79	453.93	456.90	449.02
30	42	900	544.23	531.83	549.20	538.47
35	42	1050	622.67	604.62	641.76	628.02
40	42	1200	699.61	674.36	732.28	718.21
45	42	1350	785.73	748.90	821.46	806.49
50	42	1500	864.73	808.540	909.33	897.37
100	42	3000	1664.05	1538.46	1690.68	1661.56

People prefer distances of less than 50 m to establish the condition of green corridors in the city; therefore, the green areas of the city, in relation to the hills, appear disconnected.

Figure 6 shows the spatial behavior of the urban and hill patch mosaic forming a corridor toward the hills when a lower cost distance value of 7 (210 m) is proposed in the NDVI 0.05 image LC08-L2SP-007068-20181004.

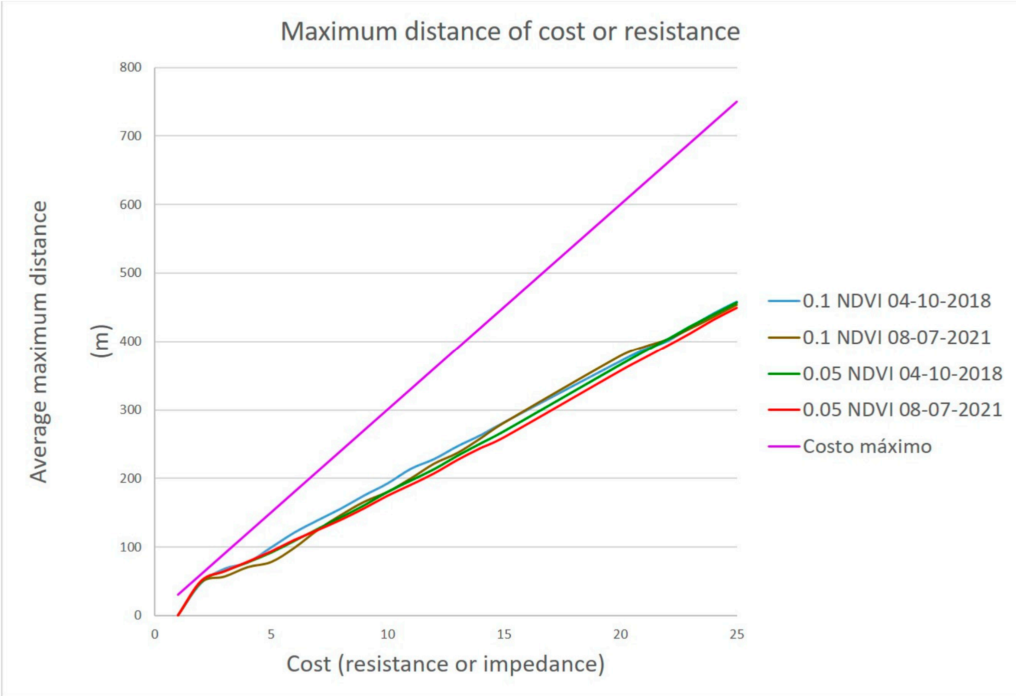

Figure 5. Maximum cost or resistance distance for two NDVIs and two months.

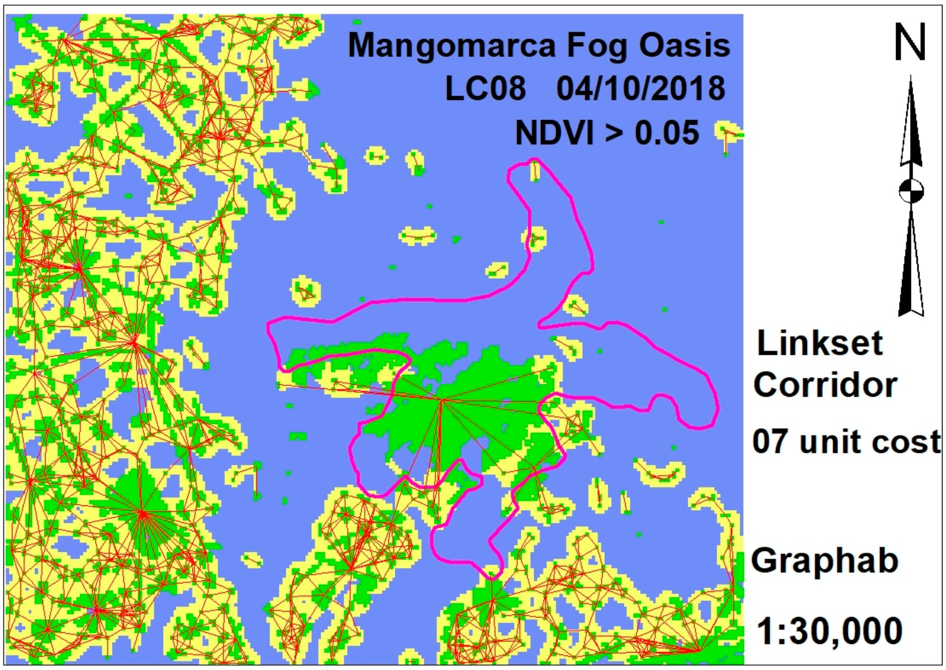

Figure 6. Cost corridor 7 for the NDVI 0.05 image from 4 October 2021 showing the patches, Linkset, and the fragile ecosystem of the Mangomarca hills.

Figure 7 shows the corridors for a cost of 10 (330 m) for the NDVI 0.01 image from 4 October 2021, and in this case, at this cost (10), no connectivity is observed between the hill and the urban area. In contrast, for the same image (NDVI 0.01 from 4 October 2021) but at a minimum cost distance of 22, connectivity is shown, as seen in Figure 8. For that drier date, vegetation patches are scarce in the hills and more abundant in the urban area (consisting of green areas and gardens).

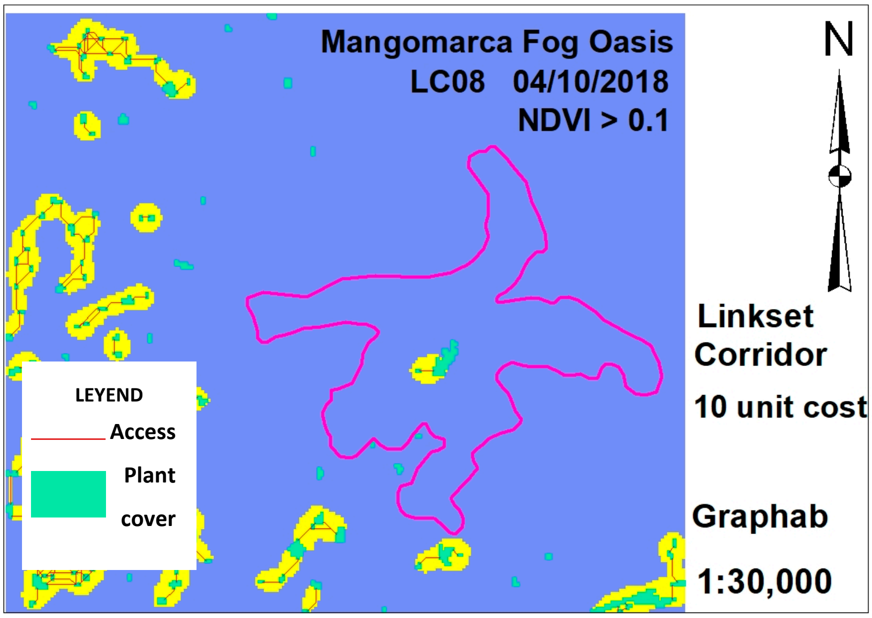

Figure 7. Cost corridor 10 for the NDVI 0.01 image from 4 October 2021, showing the patches of vegetation cover and the fragile ecosystem of Lomas de Mangomarca.

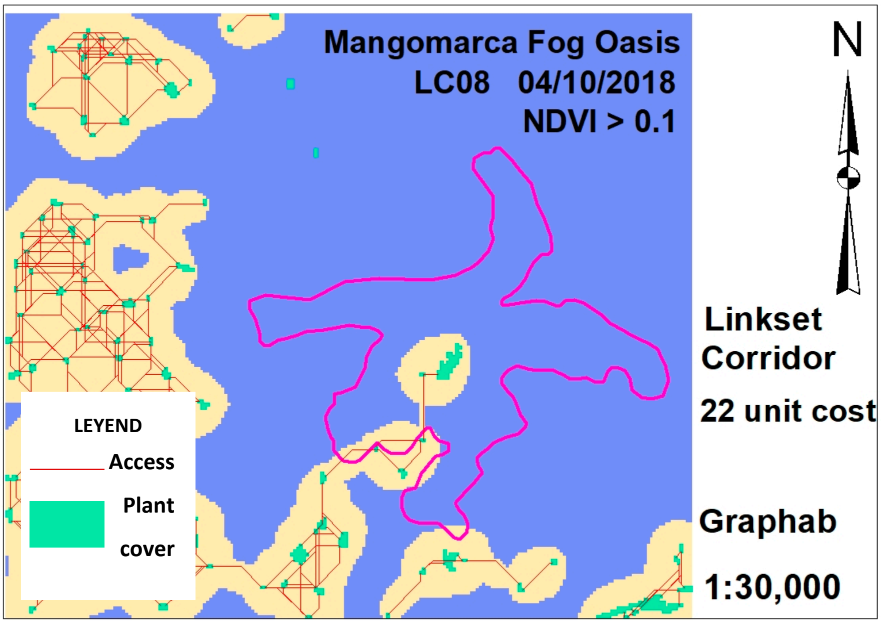

Figure 8. Cost corridor 22 for the NDVI 0.01 image from 4 October 2021, showing the patches of vegetation cover and the fragile ecosystem of Lomas de Mangomarca.

In the case of Figure 9, the corridors between the NDVI 0.05 patches are shown for the Landsat image dated 8 July 2021, at a cost of 8, where connectivity is evident. That is, somewhat similar to the case of Figure 6 for the image from 20 April 2018, NDVI 0.05, and cost 7.

The analysis highlights the importance of hillside vegetation in the area. For NDVI 0.05 on 8 July 2021 and NDVI 0.05 on 4 October 2021, the minimum cost distance is 8 (140 m) and 7 (126 m), respectively, indicating greater connectivity. However, for NDVI 0.01 (requiring patches of high greenness intensity), the connectivity is reduced to a minimum cost of 22 (400 m) and 23 (410 m), as shown in Figures 9 and 10.

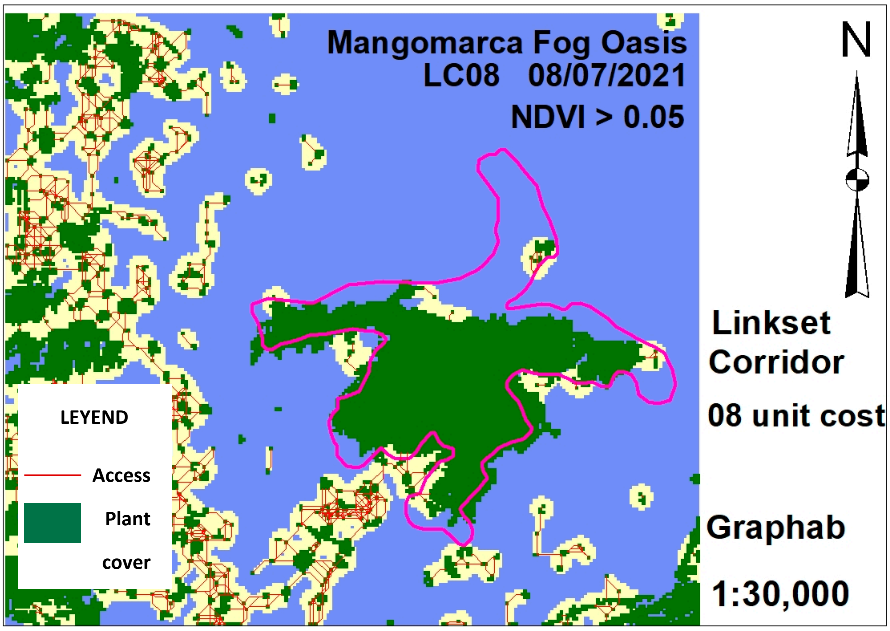

Figure 9. Cost corridor 8 for the NDVI 0.05 image from 7 August 2021, showing the patches of vegetation cover and the fragile ecosystem of the Mangomarca hills.

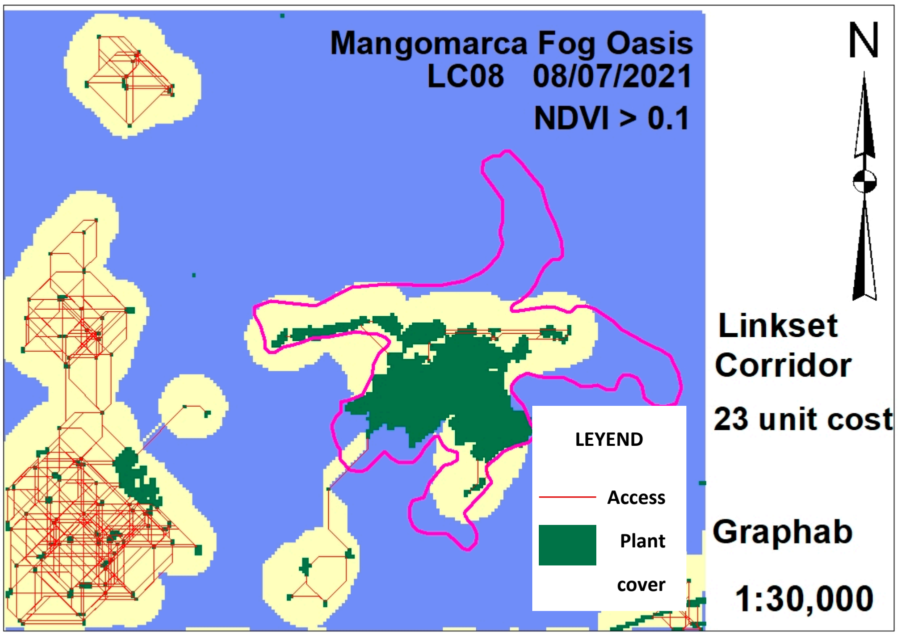

Figure 10. Cost corridor 23 for the NDVI 0.1 image from 7 August 2021, showing the patches of vegetation cover and the fragile ecosystem of the Mangomarca hills.

It would be expected that connectivity should always be at a cost of 5 (around 100 m separation between patches). At some points in the study area (toward the urban side), connected green areas are observed. Such data should be useful for urban green infrastructure planners, who should aim to reduce the separation distances between vegetation patches in the city.

Connectivity with the hills only occurs in one area (Av las Lomas), which should also be expanded to other sectors.

On the other hand, if the connectivity analysis is carried out considering the distance (m), Figures 11–14 are obtained. At smaller distances (m) between patches of green areas, there is a disconnection of the green areas. As the separation between the vegetation patches increases, the landscape appears more connected, but this type of connection implies a greater restriction (cost, impedance or environmental resistance) for a walker not willing to make the effort to walk long stretches without the presence of vegetation.

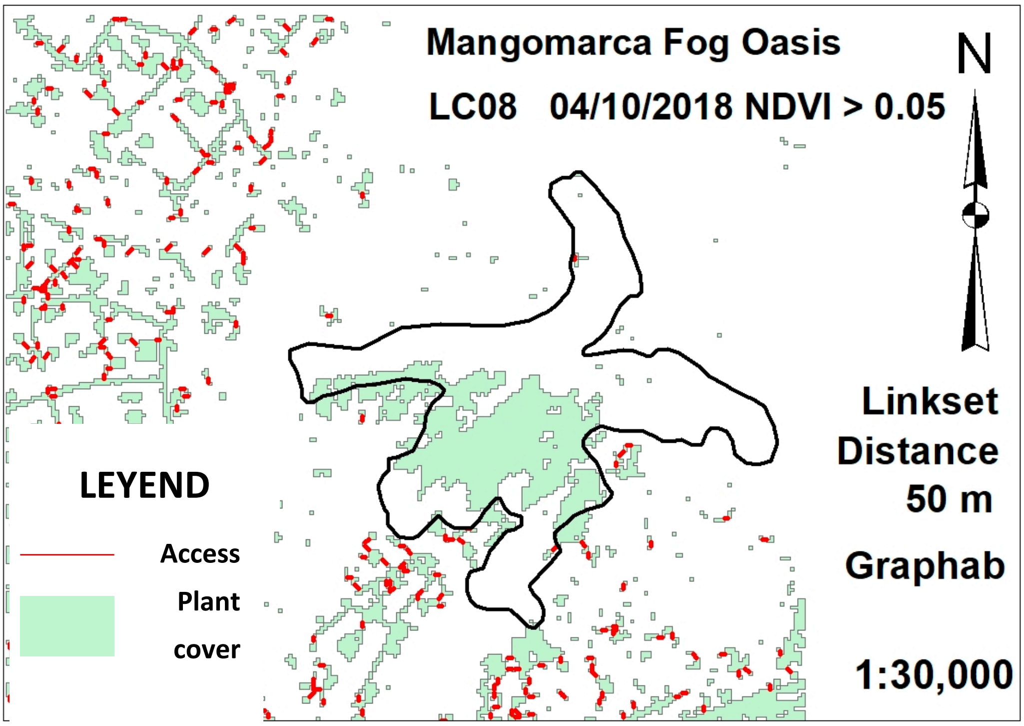

Figure 11. Links between patches of green areas 50 m apart.

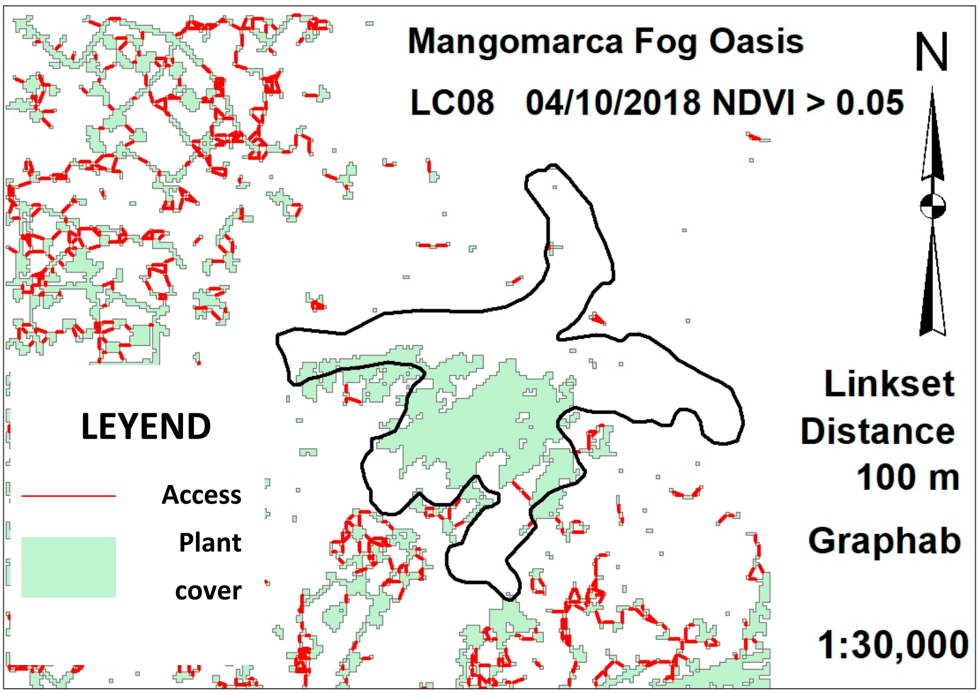

Figure 12. Links between patches of green areas 100 m apart.

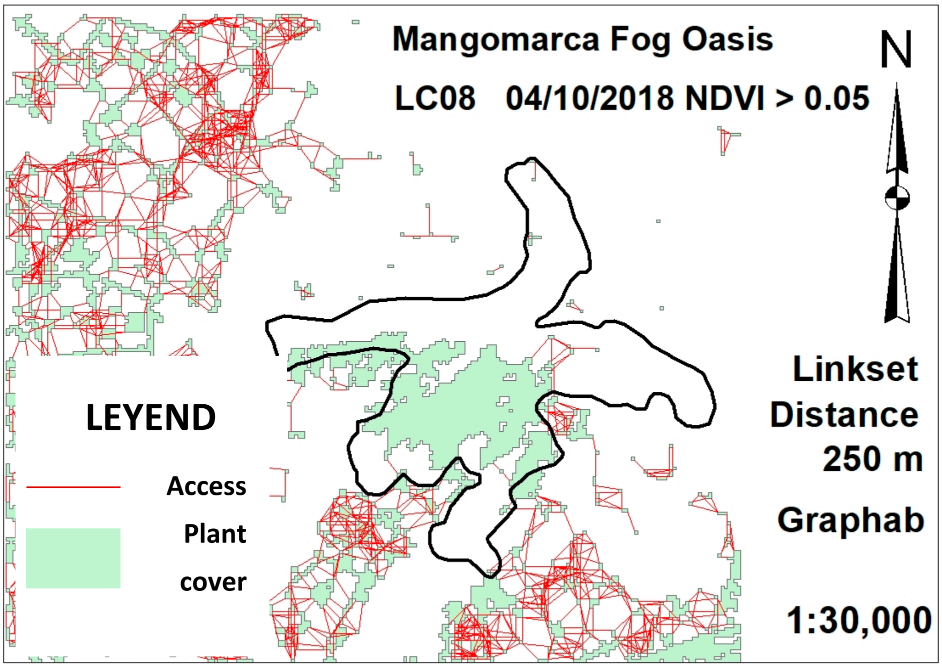

Figure 13. Links between patches of green areas 150 m apart.

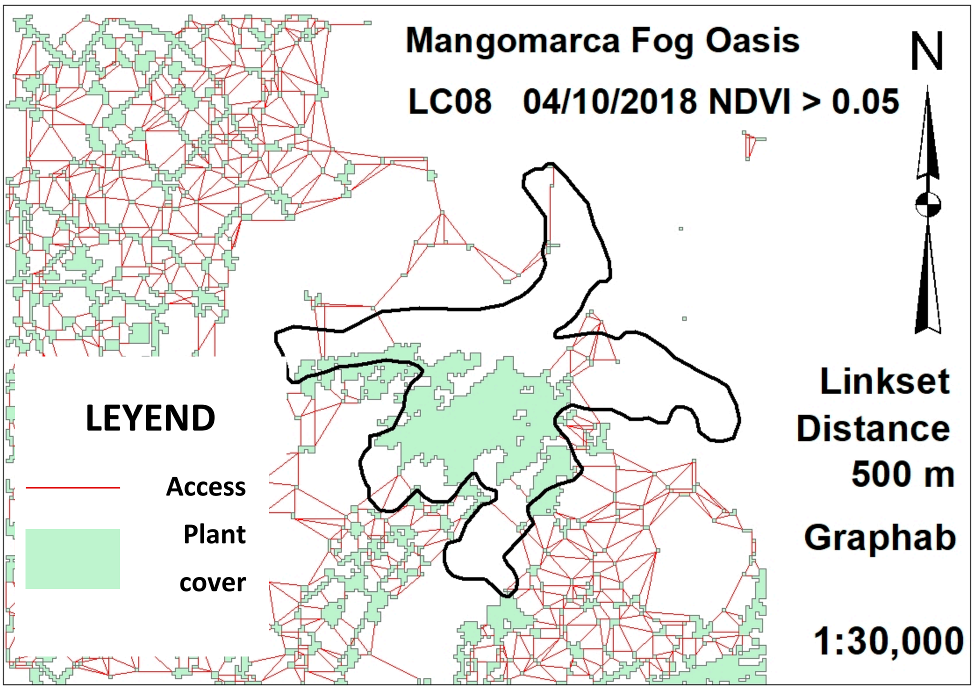

Figure 14. Links between patches of green areas 500 m apart.

3.4. Relative to the Patch Mosaic of the Greenness Intensity of NDVI 0.05

In the NDVI 0.05 images in October, the cost is 7, and in the July images, the cost is 8, which implies maximum thresholds of 210 and 240 m, respectively, with averages of 126 and 140 m, respectively. Two major clusters of vegetation are observed: Huiracocha Park and the green core of the Mangomarca hill. Figures 6 and 9 show the mosaic of vegetation patches in the study area for the NDVI 0.05 values.

3.5. Relative to the NDVI 0.1 Green Intensity Patch Mosaic

Figures 7, 8 and 10 show the mosaic of vegetation patches in the study area for the NDVI 0.1 values. For the NDVI 0.01 patches, starting from a cost of 22, connectivity is observed between the hill and urban patches in the October image (4 October 2018). This cost implies a distance range between 42 and 660 m, with an average of 400 m. That is, a threshold of 660 m (cost 22) must be overcome for two patches (hill and urban) to be connected.

For the July image (8 July 2021), connectivity occurs at a cost of 23, which implies a distance range between 42 and 690 m, with an average of 419 m. The NDVI 0.01 patches represent a higher intensity of greenery; therefore, they are fewer in number and quantity compared to the NDVI 0.05 patches, which implies a lower presence of vegetation coverage.

4. Discussion

As this research aimed to assess the connectivity between urban green infrastructure and hill vegetation, an evaluation of the connectivity of urban green areas and the connectivity within the hills (separately) was not conducted. However, indirect information was generated reflecting the degree of connectivity of such patch mosaics in urban and hill landscapes.

Given that the central problem when assessing connectivity using graph techniques lies in estimating the scale of the costs or environmental resistance, this aspect was emphasized. Table 9 contributes to new studies on the connectivity of hills and urban areas.

Since the approach assumed connectivity for an outdoor activity like walking in green corridors, as well as an ecotourism activity that could be conceived as a route starting from a central urban location like Huiracocha Park and heading through a green corridor to the Mangomarca hills, only the distance between the vegetation patches in both urban and hill areas and the hill–urban interface were considered as resistance.

Although a perception study of the population regarding the maximum distance tolerated for separation between vegetation patches in the green corridor during recreational activities was not conducted, it is likely that a tolerance range of 50 to 100 m could apply. In any case, in the present study, the distances in meters that would imply a cost scale based solely on the separation of patches (distance to be covered between two hill patches) were determined.

If the patches are very close, it would imply low costs; conversely, if the patches are far apart, it would imply higher costs as one needs to overcome a distance without observing vegetation. In this context, Table 9, covering the mean maximum distances per resistance surface for the connectivity of hill and urban vegetation patches, shows the results of the estimated costs or resistances. These values can serve as a reference for future research concerning this hill or other hills.

Since the hill greenery intensity is seasonal and, even in the urban areas, green areas undergo desiccation in the summer months, cost information should be collected for each season. Therefore, the table reflects the values for the Landsat 8 NDVI on 8 July 2023 (representative of winter climatic conditions) and 4 October 2023 (representative of end-of-hill conditions, less intense hill coverage).

The costs (resistance scale) and respective distances for the connectivity of the hill and green areas patches are evident. For the case of NDVI = 0.05 images, on 4 October 2021, a resistance must be overcome or a cost value of 7 must be assumed, equivalent to 126 m. Similarly, for NDVI $\geq$ 0.05 for the image on 8 July 2021, a cost of 8 is equivalent to 139 m.

The values of NDVI $\geq$ 0.05 correspond to the range from sparse or less intensive greenery to the highest intensity of greenery. If only the most intense greenery is considered, where the NDVI would correspond to values equal to or greater than 0.1, the cost or resistance would be 22 (399.9 m) for the image on 4 October 2021 and the cost 23 (equivalent to 419 m) for the image on 8 July 2021.

The distance data in meters correspond to an average, and the values vary, having the respective threshold as a maximum, so for cost 7, the threshold is 210 m, for cost 8, the threshold is 240 m, for cost 22 is 1205 m, and for cost 23 is 1302 m, as evidenced in Table 9.

5. Conclusions

The connectivity analysis allowed for determining the gaps in vegetation or greenery intensity between the urban area and the hills. Therefore, these areas should be prioritized for attention to increase green spaces or green infrastructure in the city.

5.1. In Relation to Structural Connectivity

- The metrics of the TMCl (patch size), NobCl (number of patches), and PerimCl are the indices that proved effective in differentiating the mosaic of urban landscape patches in relation to the hill landscape.
- The mosaic patterns of urban and hill landscapes are very different, as indicated by the landscape metrics (patch size, number of patches, and patch perimeter).
- The patch mosaics of urban and hill landscapes show differences regarding the NDVI 0.05 and 0.1 greenness intensity thresholds. As previously observed, landscapes with NDVI 0.1 thresholds exhibit fewer patches and smaller patch areas.
- IndiFrag proved effective in providing landscape metrics differentiated by classes (urban and hill in the case of this research).

5.2. Regarding Functional Connectivity

- The Graphab program proved effective in disaggregating the area of higher connectivity compared to the other, disconnected areas.
- The overall connectivity of patches in the study area ranges from 7 cost units (with a mean distance of 210 m) to 23 cost units (with an average of 410 m).

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