



Role of green roofs in urban connectivity, an exploratory approach using landscape graphs in the city of Paris, France

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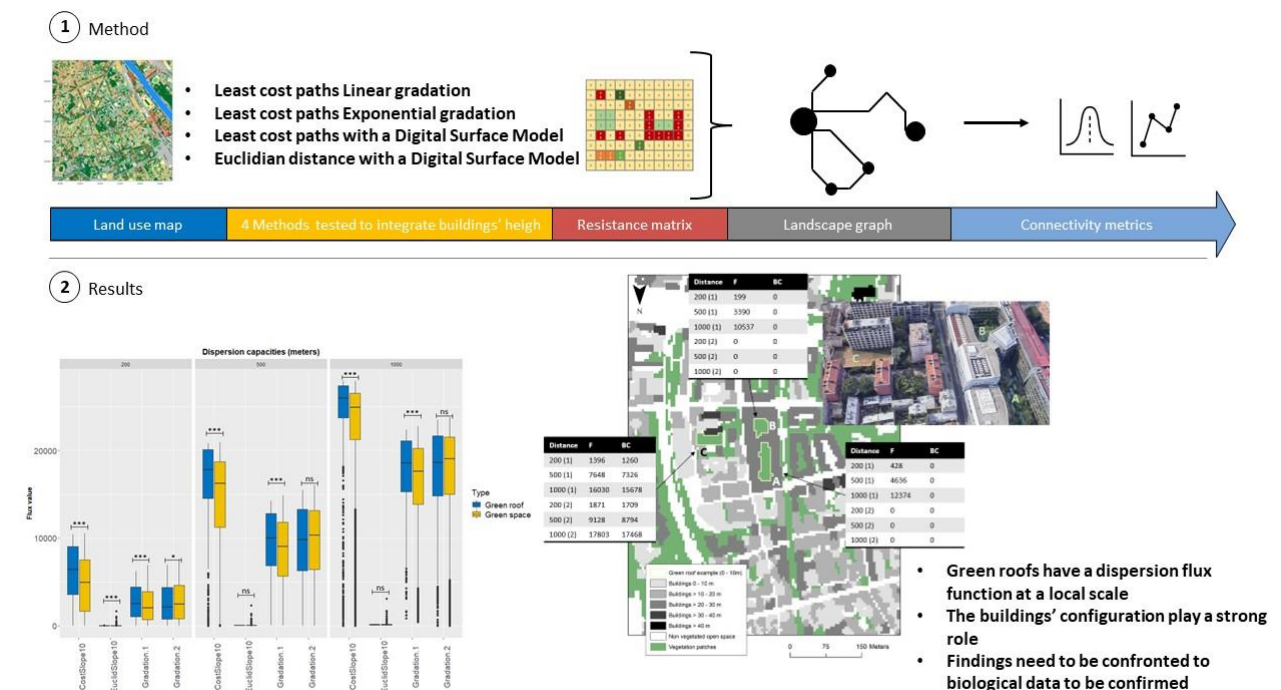
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Graphical Abstract: What is the green roofs potential role in cities' ecological networks?



Abstract

Green roofs provide many ecosystem services, but little is known about the way they contribute to urban functional connectivity. This paper has the following four objectives: (1) to compare the potential green roofs' role to connectivity in relation to other urban green spaces, (2) to specify the green roofs contribution's type, (3) to explore the influence of building height integration method and finally (4) to assess the impact on connectivity of simulated greening new roofs. Using a landscape graph approach, we modeled ecological networks of three species groups with different dispersion capacities in the Paris region (France). Then, we computed several connectivity metrics to assess the potential contribution of green roofs to functional connectivity. At a large scale (metropole scale), our results show that green roofs can slightly improve the global connectivity largely through the connections rather than the addition of habitat area. More than a stepping stone function, green roofs would have a dispersion flux function at a local scale. Furthermore, when the difficulty of crossing movement is exponential to the height of buildings, green roofs over 20 meters high are mostly disconnected from the ecological networks. In addition to the green roof's height, our analysis highlights the very strong role played by buildings' configuration. This study raises promising directions for the integration of building height into the analysis of urban connectivity. Detailed research and long-term biological data from green roofs and green spaces are needed to confirm our results.

1. Introduction

Urbanization is a major threat to biodiversity. It tends to decrease species richness (depending on taxonomic groups) because of habitat fragmentation and loss of connectivity (McKinney, 2008; Dupras et al., 2016). Thus, urban biodiversity is shaped, among other things, by the structure and permeability of the matrix (Schleicher et al., 2011; Muratet et al., 2013; Kalusova et al., 2017) in filtering the regional pool's species according to their dispersion capacities and their mobility abilities to cross it (Aronson et al., 2016). Thus, green corridors such as transport edges or vegetated pathways can provide functional connectivity (Penone et al., 2012; Vergnes et al., 2012) contrary to artificialized surfaces and buildings (Peralta et al., 2011). Improving urban biodiversity richness means in particular improving urban connectivity by creating linear or stepping stone micro-habitats between larger green spaces (Beninde et al., 2015). In cities, there are very few opportunities to create these new habitats. Therefore, walls and roofs could be seen as interesting available spaces (Jim, 2012a; Chen et al., 2020).

A green roof is a roof covered with substrate and vegetation (Blank et al., 2017). Green roofs have different design characteristics and management strategies (area, age, height, substrate type and thickness, vegetation cover, etc.) that influence the kind of vegetation growing above. Thanks to numerous studies, it is now well-known that green roofs provide many ecosystem services to city dwellers (Tratalos et al., 2007; Francis and Jensen, 2017). They participate in better rainwater management by increasing roofs' retention capacity, enhance buildings' thermal insulation, and contribute to reducing urban heat island by evapo-transpiring (Liang and Huang, 2011; Jim, 2012b; Morau et al., 2014). They can also improve buildings' aesthetics and participate to the inhabitants' well-being (Lundholm and Williams, 2015).

Concerning services to biodiversity, they offer urban species resources and habitats (Madre et al., 2013; Madre et al., 2014; Dusza, 2020) and are thus critical for biodiversity conservation (Williams et al., 2014; Lepczyk et al., 2017; Mayrand and Clergeau, 2018). Nevertheless, their contribution to the

urban ecological networks remains unclear. It depends probably on their number, size, height, and structure. However, how do these roofs' characteristics make them functional for connectivity? This question is still open, and its answer is crucial for urban managers to better plan their implementation. Actually, habitat patches are considered functional for ecological networks when they host rich communities of plants and animals and are close enough to other habitat patches to exchange individuals or propagules with each other's. Our question is therefore to examine whether green roofs can play a similar role as ground green spaces in urban ecological networks.

Comparing biodiversity on green roofs and on ground green spaces revealed that the height of roofs generally affected their hosting capacity negatively, resulting in a decrease of bee number and species richness (Braaker et al. (2014, 2017) or Tonietto et al. (2011)). The negative influence of green roofs' height was also established on the richness, abundance, and composition on a variety of other taxa (Pearce and Walters, 2012; Madre et al., 2013; MacIvor, 2016; Dromgold et al., 2020; Mills and Rott, 2020). Furthermore, Braaker et al. (2017), which is one of the only studies to analyzing the role of connectivity on species communities on roofs, showed that the community composition of highly mobile arthropods (bees, weevils) is directly influenced by structural connectivity (edge density, average Euclidean distance to the nearest habitat). In addition, they showed that the similarity of community compositions on roofs and on ground green spaces suggested vertical movements between these habitats.

Despite a large body of research on green roofs, very few studies examined their contribution to functional connectivity, even though this subject has important implications for the conservation of urban biodiversity. In this context, our paper aimed to assess the potential role of green roofs in urban ecological networks. Our approach tested the following hypotheses: (1) green roofs improve functional connectivity primarily through the additional habitat area at the city scale, (2) for the same amount of habitat, they contribute less to connectivity and (3) in a different way than ground green spaces, and finally (4), at the local scale, greening new roofs provides a highly variable contribution to functional connectivity depending on the location and the surface of the roof.

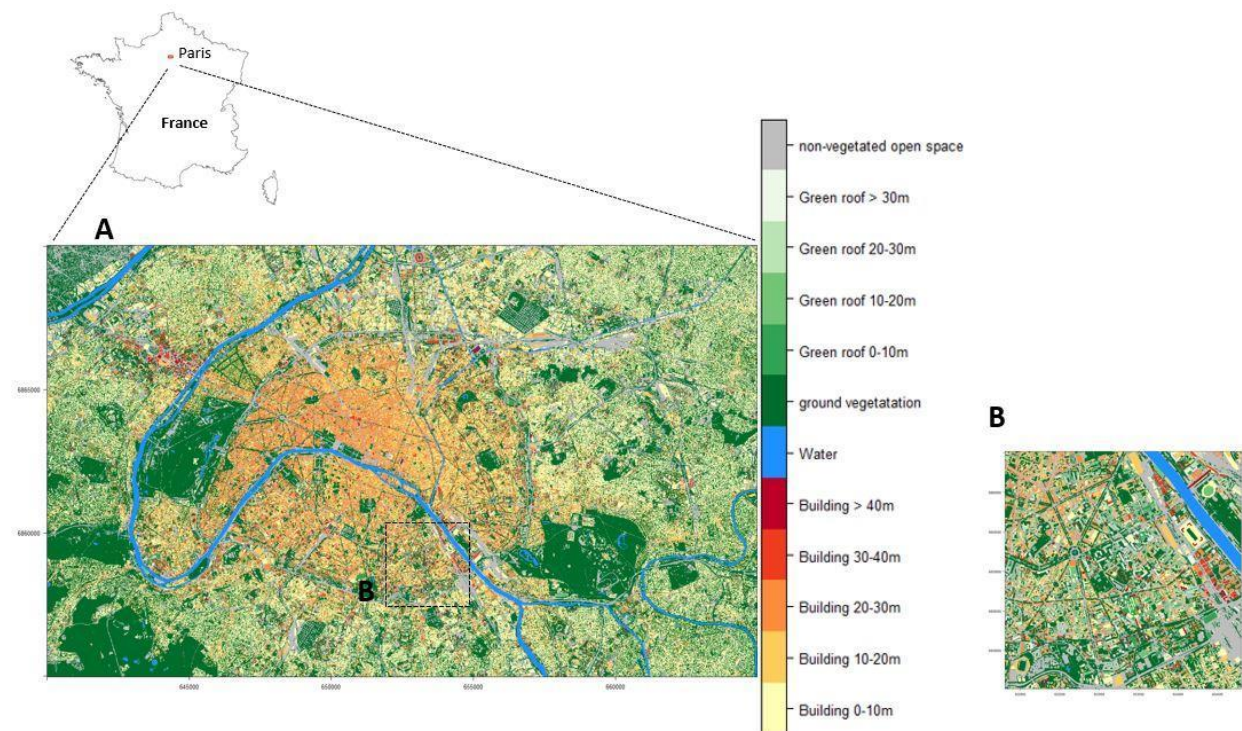
To test these hypotheses, we modeled urban ecological networks based on graph theory, which is widely used to analyze landscape connectivity (Foltête et al., 2014), such as the contribution of business green spaces in urban contexts (Serret et al, 2014), the effect of land-use changes (Sahraoui et al., 2017) and urban dynamics (Tarabon et al., 2020). As studies that consider vertical heterogeneity in urban connectivity modeling are still scarce (Joshi et al., 2021), we proposed to test four methods to integrate the buildings' height in the calculation of paths between habitat patches. Comparing the results from these four methods will allow us to determine if the way in which building height is integrated influences the distribution of roof connectivity values.

2. Method

2.1. Study area

Our study was carried out in the Paris region in France (Figure 1A). The study area covers 375 km², from the cities of Saint-Denis in the north (48° 92' 77" N, 2° 35' 70" E), Cachan in the south (48° 79' 33" N, 2° 32' 08" E), Rueil-Malmaison in the west (48° 86' 24" N, 2° 18' 21" E) and Neuilly-sur-Marne in the east (48° 85' 24" N, 2° 52' 29" E). To address hypothesis n°4, a 3km square sample was selected (Figure 1B) to reduce calculation time.

98 **Figure 1:** Study area and the corresponding 5 meter-resolution land use map of the Paris region,
 99 France. **A** is the entire study area used to test hypotheses n°1 to n°3 and **B** is a 3km square sample to
 100 test hypothesis n°4.



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103 **2.2. Land use map and species groups**

104 The land use map of the Paris region was built from the compilation of different existing databases
 105 supplemented by the creation of new data. Buildings, hydrography, and ground green spaces were
 106 taken from the open data published by APUR (the Paris Urbanism Agency). Ground green spaces
 107 include public and private vegetated areas and also agricultural areas. Green roofs were obtained by
 108 an automatic classification method based on infrared aerial images and building shapefile (Louis-Lucas
 109 et al, 2021). Finally, the non-vegetated open spaces were obtained by exclusion, i.e., what were not
 110 buildings, water, or ground green spaces. Therefore, these unbuilt and non-vegetated areas include
 111 elements of different types: roads, parking lots, bare ground. We assume that these elements can be
 112 grouped together by simplification because they are all considered as non-habitat areas, easier to cross
 113 than buildings, but more difficult than vegetated areas.

114 Based on the building height information provided by APUR, we categorized roofs into five classes for
 115 non-vegetated ones (> 0m to 10m; > 10m to 20m; > 20m to 30m; > 30m to 40m; > 40m) and four
 116 classes for vegetated ones (> 0m to 10m; > 10m to 20m; > 20m to 30m; > 30m). All green roofs over
 117 30 meters high were gathered into one group, as only one green roof was over 40 meters high.

118 The compilation of these data resulted in a 5 meter-resolution raster land use map comprising 15
 119 million pixels (Figure 1A). This resolution was a good trade-off between spatial accuracy and calculation
 120 speed. This map contained 24% of buildings, 49% of vegetation areas corresponding to 48% of ground

vegetation and less than 1% of vegetated roofs, 24% of non-vegetated open spaces and about 3% of water surface.

Three species groups with different dispersion capacities were considered, as in Serret et al. (2014): 200 meters for low-mobility species such as barochorous plant or some solitary bees like *Chelostoma florissomme* or *Osmia bicornis* (Hofmann et al., 2020), 500 meters for medium-mobility species such as entomogamous plants or in a number of butterfly species like *Polyommatus icarus* and finally 1000 meters for highly mobile species such as anemogamous species or some wild bees like *Chelostoma rapunculi* (Zurbuchen et al., 2010).

2.3. Ecological networks modeling by integrating buildings' height

From this land use map, the ecological networks for the three groups of flying organisms (animals or plants) were modeled based on landscape graphs using Graphab 2.8 software (Foltête, 2021). A landscape graph consists of habitat patches represented by points (nodes) and connected or not by links indicating a functional connection, i.e. a flow between two patches (Urban et al., 2009). In our study, habitat patches were defined as a set of adjacent vegetation pixels with an area of at least 100 m² to reduce calculation time. Links were defined in planar topology and following four different methods to integrate building height in the calculation. Following the literature that showed a negative effect of height on biodiversity, the four methods were based on the same principle: assigning an increasing resistance according to building height.

In the first three methods, links were calculated using least-cost paths to integrate the resistance of the landscape matrix. Therefore, each type of land use had a cost or resistance value that referred to its permeability for species movement (Table 1). Ground green spaces and water areas had the lowest resistance value (1) and non-vegetated open spaces had a resistance value of 5, meaning that they were easy to cross for flying organisms. The resistance to cross buildings depended on many parameters such as urban configuration, microclimate, and species dispersion capacities. Thus, we built two resistance gradations to consider this variability suggested by Pearce and Walters (2012), Madre et al. (2013), MacIvor (2016), Dromgold et al. (2020), Mills and Rott (2020).

In the first method (named "gradation 1"), the resistance increased linearly with the building's height, from a cost of 10 for the lowest to 50 for the highest buildings. The second method ("gradation 2") assumed that the cost increased exponentially with the building's height, from 10 to 100,000. The third method ("Costslope10") combined cost values and an additional weight according to the height of the building. Already tested to weight least-cost paths according to slope in mountainous areas (Mimet et al., 2016), we proposed here to apply the same method in urban areas by using a digital surface model. The cost of habitat patches is set to 1, non-vegetated spaces to 5 and buildings to 50. Then, a coefficient of 10 was arbitrarily multiplied by local slope to increase the cost according to the height differences. This weight favored paths occurring at the same height, whether at ground level or higher. Conversely, it made vertical paths costlier. Finally, the last method ("Euclidslope10") is based on Euclidian distance between patches (i.e., all land use types had the same cost) and a slope weight following the same parameter as before.

Table 1: Resistance values for each land use type according to the four methods. In the gradations 1 and 2, the resistance increased respectively linearly and exponentially with building's height. Thus, there were no difference between the two gradations for ground level structures i.e., water surfaces, green spaces and non-vegetated open spaces. In

Costslope10, the costs of land use types were weighted according to slope intensity. In *Euclidslope10*, the cost of each pixel was only related on the slope weigh, regardless of the land use types.

Code	Land use types	Gradation 1	Gradation 2	Costslope10	Euclidslope10
1	Buildings (> 0-10 m)	10	10	50	NA
2	Buildings (> 10-20 m)	20	100	50	NA
3	Buildings (> 20-30 m)	30	1,000	50	NA
4	Buildings (> 30-40 m)	40	10,000	50	NA
5	Buildings (> 40 m)	50	100,000	50	NA
10	Water surfaces	1	1	1	NA
20	Green spaces	1	1	1	NA
30	Green roofs (> 0-10 m)	10	10	1	NA
31	Green roofs (> 10-20 m)	20	100	1	NA
32	Green roofs (> 20-30 m)	30	1000	1	NA
33	Green roofs (> 30 m)	40	10,000	1	NA
50	Non-vegetated open spaces	5	5	5	NA

For simplification purpose, we selected gradation 1 and 2 corresponding to linear and exponential resistances to explore the results of the global and the prospective analysis. The four methods were mobilized in the local analysis (corresponding to 3.2) to compare the results of green roofs' connectivity's contribution.

2.4. Connectivity metrics and data analysis

2.4.1. Contribution of green roofs to global connectivity (metropole scale)

To identify the contribution of green roofs to global connectivity, we modeled ecological networks from two land use maps: the first one without green roofs (i.e., all green roofs were considered as non-vegetated buildings); the second one with green roofs. Two link sets were calculated on each of these two graphs using the linear (gradation 1) and exponential (gradation 2) resistance gradations. The probability of connectivity (PC metric) was calculated at three distances (200, 500, 1000 m) on these two graphs to carry out a comparative analysis. Saura and Rubio (2010) define the PC as "the probability that two randomly placed points in the study area are located in interconnected habitats":

$$PC = \frac{\sum_{i=1}^n \sum_{j=1}^n a_i \times a_j \times p_{ij}^*}{A^2}$$

Where n is the total number of patches, a_i and a_j the area of patches i and j and A the total area of the study area. P_{ij} represents the probability that i and j are connected by a link. P_{ij} can be calculated as follows:

$$p_{ij} = e^{-\alpha d_{ij}}$$

Where d_{ij} is the least-cost path between patches i and j and α ($0 < \alpha < 1$) expresses the decrease in dispersion probabilities resulting from this exponential function (Saura & Pascual-Hortal, 2007).

The PC metric considers both habitat area and connections between habitats. To determine whether the contribution to connectivity of green roofs is related to their area, their connections, or both, the

PC is calculated once with green roof area (i.e., a_i equal to the area of the patch i), and again without area (i.e., $a_i = 1$).

2.4.2. Contribution of green roofs to local connectivity (patch scale) and effect of buildings' height

To understand the type of contribution of green roofs to local connectivity and to compare it with green spaces, we calculated two local metrics on the graph modeling the ecological network with green roofs, using the four links calculation's methods. The Betweenness Centrality (BC) (Bodin & Saura, 2010) highlights the patches with a strategic position in the network. This metric is the sum of the shortest paths between each pair of patches weighted by their interaction probability:

$$BC_i = \sum_j \sum_k a_j^\beta \times a_k^\beta \times e^{-\alpha d_{jk}}$$

The Flux (F) highlights well-connected patches, as the more connected a patch is to many other patches, the higher the value of F. This metric represents the sum of the capacities of the patches connected to a focal patch and weighted according to their minimum distance to the focal patch through the graph:

$$F_i = \sum_{j=1}^n a_j^\beta \times e^{-\alpha d_{jk}}$$

For both metrics, a_j (the area of patch j) is weighted by the parameter β . As the green roofs' surface area is much smaller than green spaces' area (Table 2), the parameter β was set to 0 to ensure that comparison was not biased by differences in area between the two categories.

2.4.3. Prospective analysis: effect of greening new roofs on connectivity

The prospective analysis consisted of prioritizing new roofs to be vegetated according to their potential contribution to functional connectivity. The database of roofs to be greened (unobstructed roof and slope below 2%) was formerly constructed by APUR (2013) throughout the city of Paris.

The method consisted in (1) calculating the global metric PC quantifying the initial connectivity from the land use map including existing green roofs, (2) simulating the greening of one new roof (i.e., adding a new habitat patch) and recalculating the PC, (3) repeating this operation for each potential roof contained in the APUR database and then, (4) incrementing the PC variation brought by the addition of a new roof in its attributes. This prospective analysis was conducted to a smaller study area for time calculation reasons (Figure 1B).

3. Results

The resulting land use map included a total of 41,065 habitat patches with a median area of 4,400 m². 95% of those patches were ground green spaces and represented 99% of the vegetated area (in m²) (Table 2).

Table 2: Statistical description of green roof and ground green space patches in the entire study area (Figure 1A).

Code	Land use	Mean Area (m ²)	Sd Area (m ²)	N patches	Area prop (%)
30	Green roofs (> 0-10m height)	1127	2525	1233	0.37
31	Green roofs (> 10-20m)	1790	2875	447	0.21
32	Green roofs (> 20-30m)	2352	3349	131	0.08
33	Green roofs (> 30m)	2692	4359	23	0.02
20	Green spaces	4550	170065	39231	48

3.1. Contribution of existing green roofs to global connectivity

Comparison of the ecological networks from the two land use maps (by excluding or including green roofs) showed that green roofs increased the probability of connectivity by 1 to 2% when the patch area was considered, depending on the resistance gradation and the dispersion capability of species (Table 3). When all patches' area was set to 1, green roofs increased the probability of connectivity from 10.9 to 12.9% with linear resistance gradation, and from 9.8 to 10.4% with exponential resistance gradation.

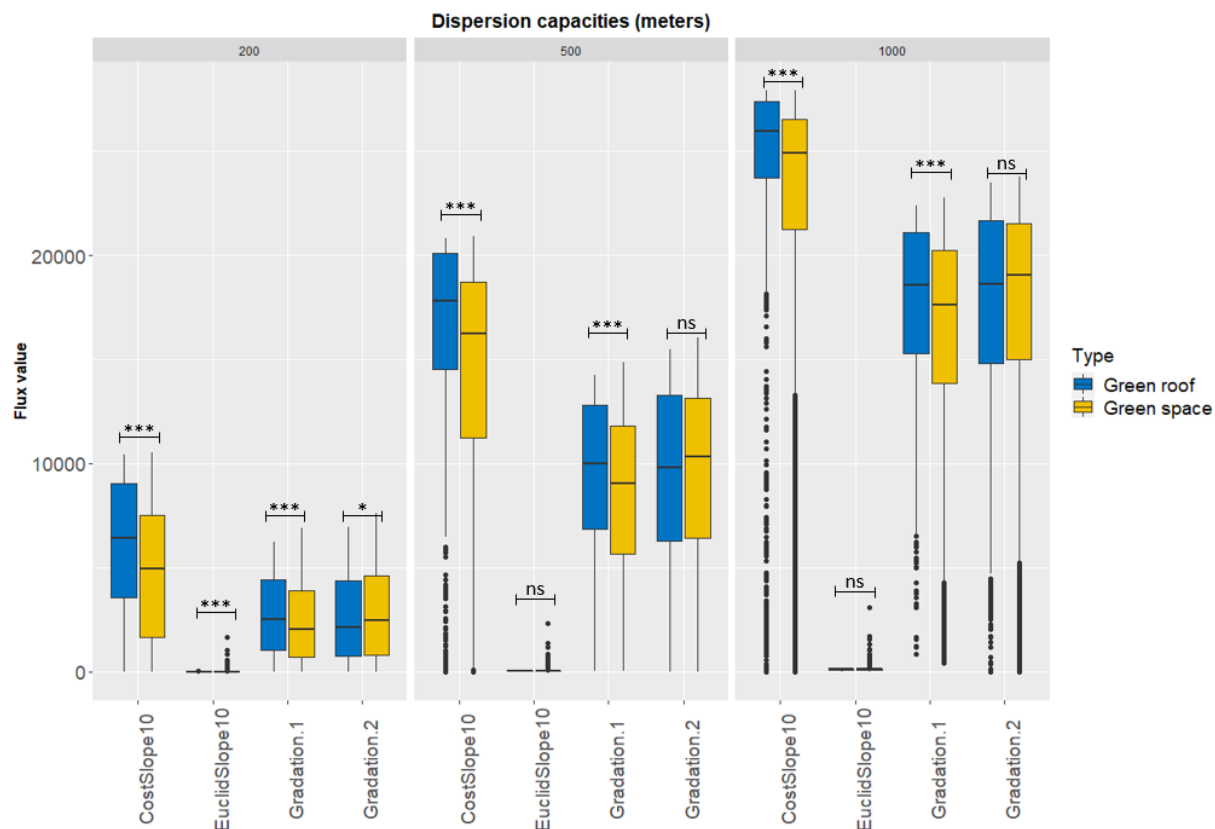
Table 3: Global connectivity rate of change measured by the probability of connectivity (PC) including or excluding green roofs for the two resistance gradations and the three groups of species according to their dispersion capacity. (A): a_i is the surface of the patch i ; (B) :the area of all patches set to 1.

Distances	with/without green roof – gradation 1		with/without green roof – gradation 2	
	a_i =area (A)	a_i =1 (B)	a_i =area (A)	a_i =1 (B)
200	1.87%	12.95%	1.49%	10.44%
500	2.46%	11.75%	2.07%	10.15%
1000	2.69%	10.92%	2.35%	9.86%

3.2. Type of contribution to connectivity of green roofs vs. ground green spaces

The distribution of F and BC values for green roofs and ground spaces were compared for each of the four link calculation methods (Figure 2). CostSlope10 had the highest values for the two metrics. Gradations 1 and 2 had slightly smaller (almost half as much) and relatively close values. On the other hand, EuclidSlope10 had the lowest values for both metrics. With gradation 1 (linear) and CostSlope10, the average F values were higher for green roofs than for ground green spaces for all species groups. With gradation 2 (exponential) and EuclidSlope10, the average F values of ground green spaces were always higher, but the difference was not significant. With gradation 2, ground green spaces have higher values of 2% for all dispersion distances. Conversely, for EuclidSlope10, the ratio decreased from +11% for 200 m to +1% for 1000 m.

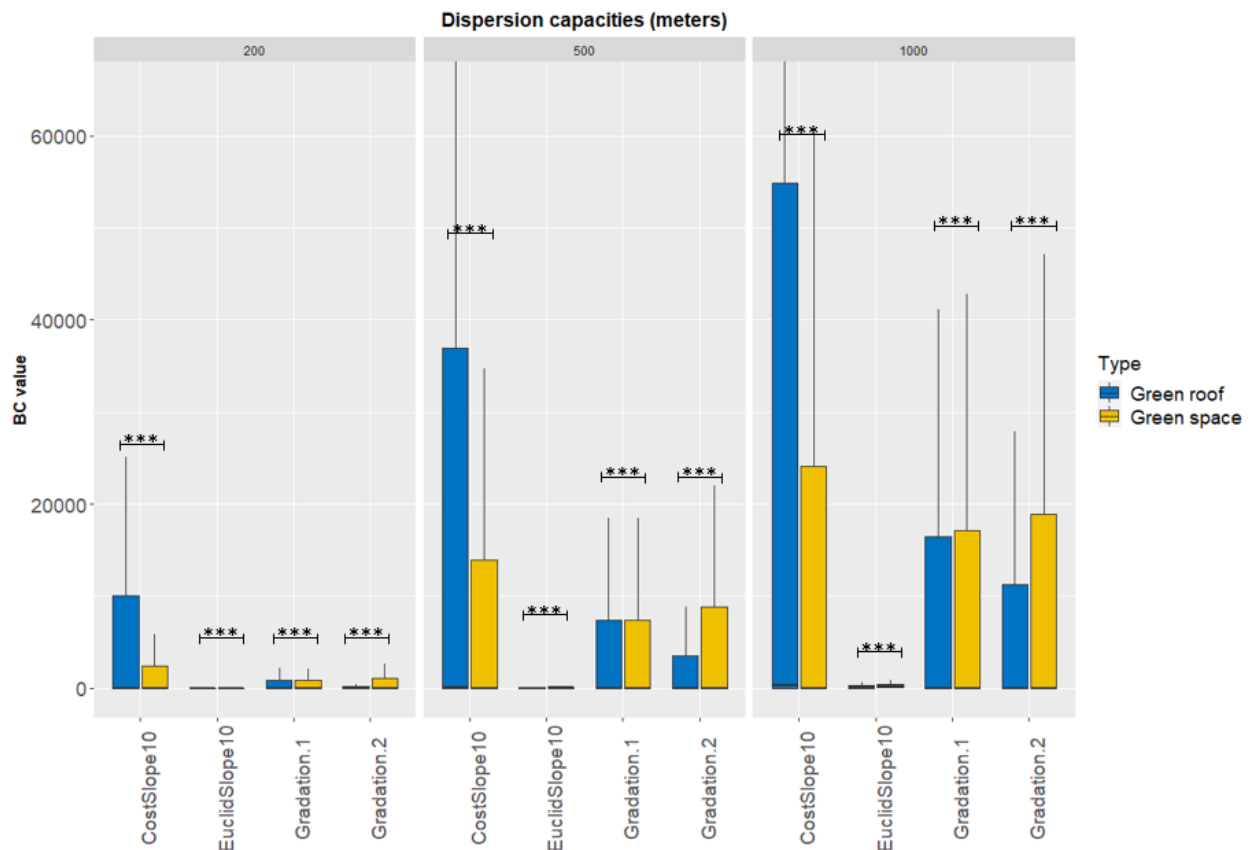
Figure 2: Comparison of the Flux (F) values between green roofs and ground green spaces for the four resistance gradations and the three dispersion capacities. Stars represent significance levels from Wilcoxon's test.



248

249 There was a strong difference between the average BC values for green roofs and ground green spaces,
 250 regardless of the species dispersion capacity and the four methods we tested (Figure 3). With
 251 CostSlope10, the average BC value for green roofs was 43% higher than ground green spaces.
 252 Conversely, for the three other methods, it was significantly smaller. With gradation 1, and for low-
 253 mobility species (200 m), the average BC value for ground green spaces was 4.39 times higher than for
 254 green roofs, whereas high-mobility species (1000 m) this difference was 4.81 times higher. With
 255 gradation 2, the average BC value (dispersion 200 m) for ground green spaces was 5.4 times (200 m)
 256 and 5.58 times (1000 m) higher than for green roofs. For both gradations, the gap between green roofs
 257 and ground green spaces shrank with increased dispersion capacities.

258 **Figure 3:** Comparison of the BC (Betweenness centrality) values between green roofs and ground green
 259 spaces. Only 90% of the values were represented (quantile from 5 to 95). Stars represented significance
 260 levels from Wilcoxon's test.



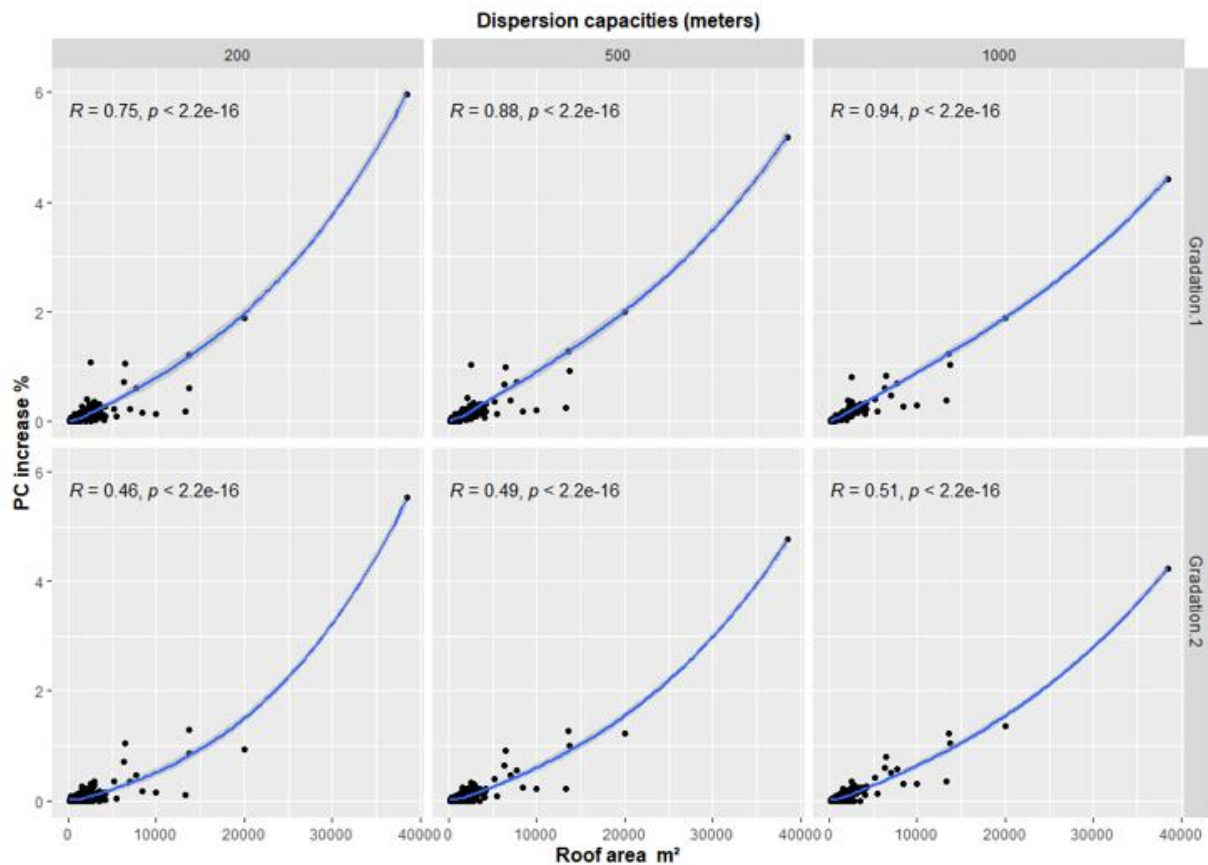
Many green roofs had a zero BC value, meaning they were not central in the network (Appendix A): 31% with EuclidSlope10, 47% with CostSlope10, 56% with gradation 1 and 65% with gradation 2. As comparison, the proportion of zero values was lower for ground green spaces except with CostSlope10 (53%). Concerning F values, none of the green roofs had a zero value with gradation 1 and EuclidSlope10, while 2% of the green roofs were completely isolated from the network ($F = 0$) with gradation 2 and less than 1% with CostSlope10. As comparison, none of the ground green spaces was disconnected from the network with gradation 1 and EuclidSlope10 (whatever the dispersion capacities), less than 2% with gradation 2 and 3% with CostSlope10. This suggested that green roofs contributed more to connectivity in terms of dispersion flows through connections with other roofs and green spaces than in terms of centrality.

3.3. Contribution of new potential green roofs on connectivity

For simplification purpose, we selected gradations 1 and 2 corresponding to linear and exponential gradations to analyze the contribution of new potential green roofs to connectivity. We tested 722 new potential green roofs in an iterative way. Regardless of the gradation, the large majority of the tested roofs provided a very light PC gain. Indeed, 90% of them brought a gain of less than 0.1% in linear resistance gradation and for low-mobility species (Figure 4). This percentage tended to decrease with increasing species mobility, reaching 80.8% for high mobility species. In the same way, in exponential resistance gradation, this value decreased from 93.6% to 89.6%, depending on the group of species. One roof maximized the probability of connectivity (PC) for both resistance gradations and the three groups of species (see Appendix C). This roof had a low height, less than 10 meters (land use code = 30) and corresponded to the largest one (about 38,400 m²), i.e., an esplanade situated a few

meters above the ground. Greening this roof would increase the PC from 4.2% (gradation 2, 1000 m) to about 6% (gradation1, 200 m).

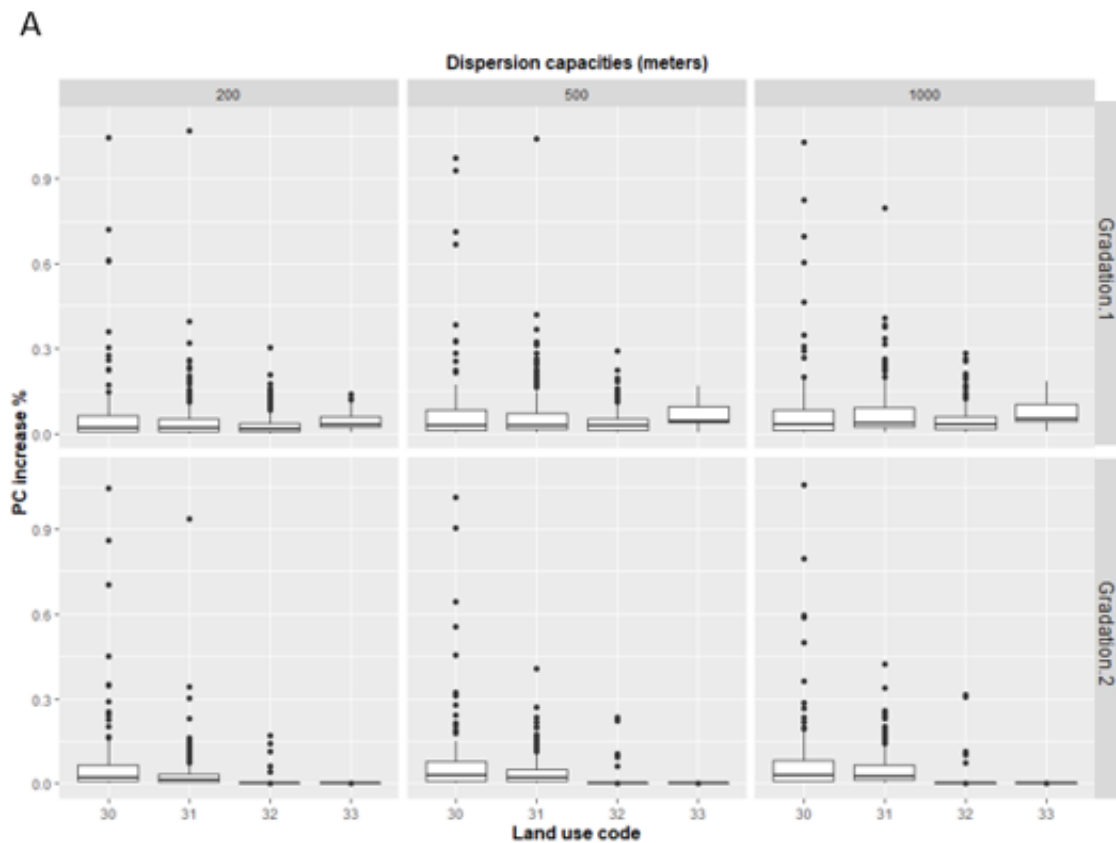
Figure 4: Potential gain in probability of connectivity (PC) from greening new roofs according to their area (m²), the dispersion capacities of species, the resistance gradations 1 or 2. R and P-value corresponding to the Spearman correlation test.



The gain in probability of connectivity (PC) provided by new green roofs was partly explained by their area as shown in Figure 5. The two parameters were strongly correlated, especially in gradation 1 (from R=0.75 to 0.94).

The height of the buildings tested was also a driver for the PC increase, especially in gradation 2 (Figure 5). Indeed, with this gradation, we observed a significant negative correlation between building height and PC increase for all species groups (Rho between -0.74 and -0.76). Conversely, there was no significant correlation between building height and PC increase in gradation 1.

Figure 5: Potential gains in probability of connectivity (PC) from greening new roofs according to their height, the species dispersion capacities and the resistance gradations (A), associated to Spearman's correlation, and p-value (B). The graph is here centered on PC values between 0 and 1 to make it more readable. 5 values exceed 1%, all for roofs between 0 and 20 meters high, i.e., Land use codes 30 and 31). **30:** green roofs > 0-10 m; **31:** green roofs > 10-20 m; **32:** green roofs > 20-30 m; **33:** green roofs > 30 m.



B

Gradation	Dispersion capacities	P-value	Rho
1	200	0.6	0.019
1	500	0.37	0.03
1	1000	0.26	0.04
2	200	2.2e-16	- 0.76
2	500	2.2e-16	- 0.75
2	1000	2.2e-16	- 0.74

4. Discussion

This paper intended to understand green roofs' effective and potential roles in urban ecological networks by using an original approach based on landscape graphs.

4.1. Green roofs contribute to connectivity but differently from ground green spaces

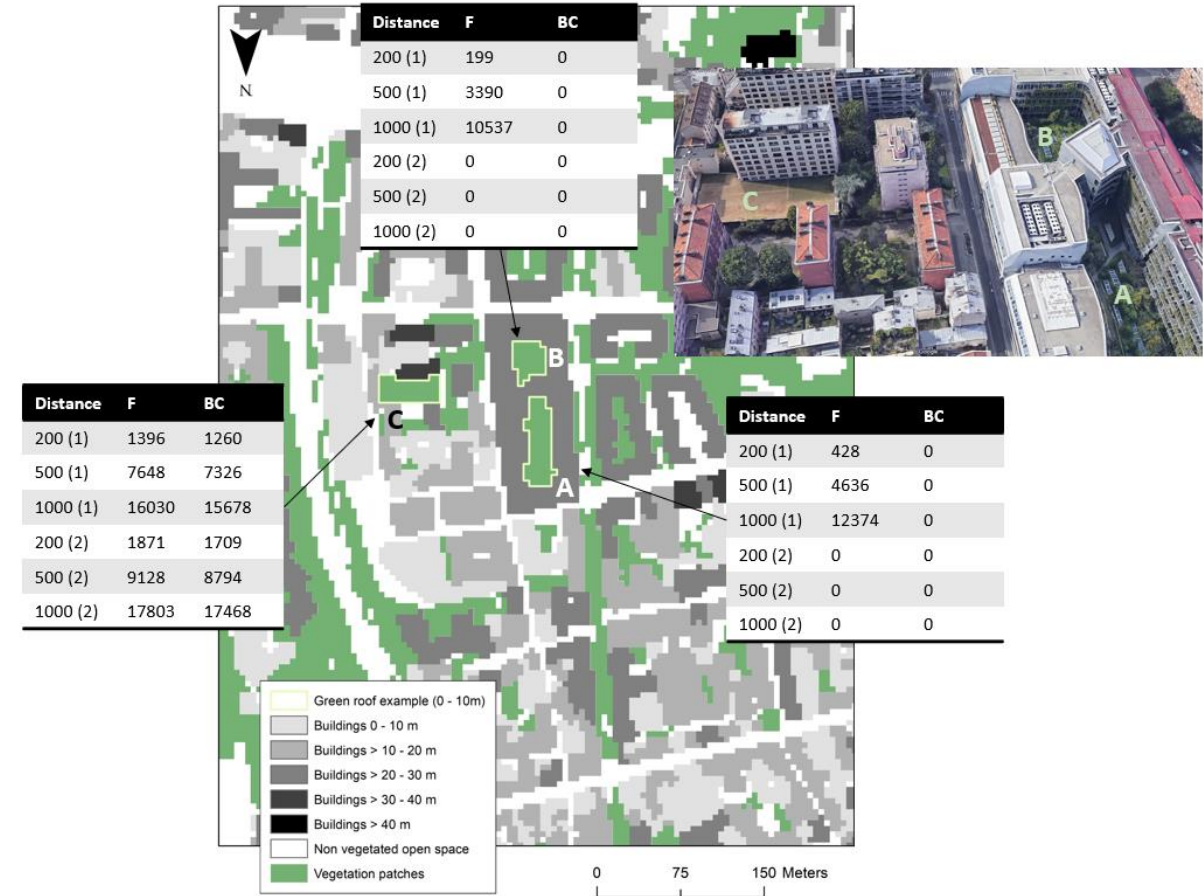
At a global scale, our results suggest that green roofs contributed significantly to landscape connectivity. Thus, despite their small cumulative area compared to ground green spaces (less than 1% of the total vegetated area) their contribution should not be minimized. The highest impact of green roofs on connectivity when PC was calculated without 'area' suggests that their contribution is more linked to network topology (i.e., connectivity *per se*) than to habitat amount. Surprisingly, while the PC gain increases with increasing dispersion capability when patch capacity is equal to area (i.e., a_i equal to the area of the patch i), the PC gain is less strong as the distance increases (13% for 200 m to 11% for 1000 m with gradation 1, Table 3) when the area of patches is considered as identical ($a_i=1$).

At the patch scale, green roofs often have higher Flux values (Figure 2) and lower BC values (Figure 3) than ground green spaces. This suggests that they have more of a role in terms of dispersal flows than as connectors between habitats, especially for relatively and highly mobile species. Nevertheless, this can be qualified because for one of the methods (Costslope10), the BC values of green roofs are much higher than ground green spaces (Figure 3).

4.2. Height and building configuration strongly affect connectivity

The highest green roofs have the lowest mean connectivity values, whatever the resistance gradations, the group of species or the metric used for calculation (Appendix E). These results are logically explained by the parameterization of the resistance according to the height (Table 1). But surprisingly a large portion of low green roofs do not have a strategic position in the network (high proportion of null BC values) that can be explained by urban configuration. Some ground green spaces and low green roofs (patches A and B on Figure 6) are surrounded with high buildings, limiting connections to nearby green spaces. By contrast, open green roofs (patch C on Figure 6) seem to be more connected. We therefore hypothesize that urban configuration plays a strong role on connectivity. It could explain why some studies (Blank et al., 2017; Kyrö et al., 2018) could not find height as a significant parameter to explain community composition on green roofs. It can be assumed that low roofs at city scale are often surrounded with high buildings (in a situation comparable to patches A and B in Figure 6). We can extrapolate this assumption for urban green spaces, which could explain why more than 40% of green spaces do not have a strategic position in the network.

Figure 6: Impact of building configuration on the contribution of green roofs to connectivity. *Extract from the land use map (Figure 1) and aerial image from google maps, 2021. A, B, C are three green roofs in eastern Paris. F (flux) and BC (betweenness centrality) are the connectivity metrics presented in the method section.*



Nevertheless, our results should be taken with caution, as zero flux values do not necessarily mean that these low roofs have no role in the ecological network. As can be seen in Figure 6, there are vegetated balconies we did not consider in our modeling. Actually, integrating green walls into modeling was too challenging, but we cannot exclude that such green elements could facilitate species movement and thus contribute to urban connectivity (Mayrand & Clergeau, 2018). Nevertheless, our results enable us to better understand the key role of urban configuration on connectivity, which is currently under-researched (Flégeau, 2020).

4.3. Contributions and perspectives for urban connectivity evaluation

One of the challenges of this analysis was to propose a new framework for analyzing ecological networks in cities, especially with the consideration of building height. The four methods proposed have been parameterized in such a way as to increase the resistance as the height of the building increases. Only the shape of the increasing function varies. The first two methods (gradation 1 and 2) group buildings and vegetated roofs into different resistance classes according to their height. The third method (Costslope10) uses least-cost paths weighted by the slope according to the height of the buildings. Finally, the fourth one (EuclidSlope10) uses Euclidian distance between habitat patches, weighted by the slope. Thus, one would expect the F and BC values of the roofs to have a similar distribution regardless of the method. However, we observe strong variations in the distribution of connectivity values according to the roof height. While the proportion of null values of BC increases logically with height for gradation 2 (Appendix B), it decreases on the contrary for Costslope10. For

Euclislope10 and gradation 1, the variations are not progressive, with more zero BC values at intermediate heights (0-10m and 10-20m). Concerning the difference between green spaces and green roofs (Figures 2 and 3, appendix D), we observed that the EuclidSlope10 method and exponential gradation have roughly the same effect. On the other hand, Costslope10 seems to be very different with higher centrality values for green roofs than for ground green spaces. There should be a lot of ground green spaces surrounded by buildings considered as very important obstacles in this method. It could explain the higher values of BC and F for green roofs compared to ground green spaces. This variability in results pays attention to how the height of landscape features is incorporated into connectivity models.

Since our approach is exploratory, we made some unavoidable simplifying choices. First, we choose a resolution of 5m for the land use map. This resolution was determined after several tests to find the best compromise between accuracy and calculation time. As the minimum size of roofs is 100m², a resolution of 25m² seemed sufficiently precise to capture these elements, as well as the other urban landscape elements such as roads or the shape of building (Figure 6). If this resolution seems sufficient for the metropolitan scale, it would be interesting to test a finer resolution for local analyses, especially since the used data on vegetation are available at very high resolution (i.e. 0.50m).

Second, we considered all vegetated areas as homogeneous, which is far from the reality. We could have qualified vegetation by its vertical stratification (Casalegno et al., 2017), or weighted habitats' quality by their age, composition, or thickness of the substrate (for roofs), which can modify plant communities' properties (Dunnett et al., 2008; Dusza et al., 2017; Kyrö et al., 2018). We think it will constitute the next step of the work.

Third, we considered the increasing crossing difficulty as a function of height. It is probably true, but the shape of the function is unknown and driven in a complex way by multiple factors. For example, Vergnes et al. (2017) showed that roof height could have a positive effect on seed, spider, and insect abundances when the Landscape Greening Index (based on NDVI) is high. They hypothesized that low density of high buildings benefited to aerial plankton dispersion.

To confirm our results and explore the variability of results according to the height integration methods, it would be particularly interesting to confront the results with biological data. As already explained, the approach we developed is exploratory and theoretical. We should now combine potential connectivity to biological responses, which is currently rarely done in graph-based modeling (Foltête et al., 2020). This would require long-term monitoring of green spaces and roofs at various heights to follow abundance and richness of plant and animal species. In addition, this experimental setup could test the effect of building configuration.

Even if further studies are necessary, these preliminary results already provide interesting keys for decision-makers to implement new green roofs or to reconnect some green spaces to ecological networks. Despite a positive effect of green roofs on urban connectivity at an overall scale, a local analysis helps optimize those benefits by considering building configuration.

According to our results, with the parameters we used, we advise decision-makers to implement green roofs with a height of less than 20 meters (approximately 6-level buildings) with an open building configuration towards other green spaces. We are aware that this threshold height is derived from the choice of parameters we have made for our modeling. Nevertheless, our work shows that, below a specific height, roofs should be dedicated to biodiversity and ecological networks through adapted

vegetation. Above this threshold, other types of roofs can be implemented such as solar panels. In any case, in any urban project, integrating ground green spaces is always a priority because they are essential for urban connectivity. Low green roofs should be considered as complements for more functional ecological networks.

5. Conclusion

Even if their role is weaker than ground green spaces, green roofs' contribution to connectivity should not be minimized because we demonstrated that they are significant at different scales. Through our analysis, we established that they have more of a dispersion than central role in urban ecological networks, but they can have an importance, particularly in city centers where green spaces density is often low.

The approach we developed should be continued and new methods to integrate building height should be tested. Integrating other variables would be also necessary to increase our models' accuracy. The design of methods for analyzing connectivity in 3D is a major challenge, as highlighted by Foltête et al, (2021). Moreover, as our approach is exploratory and theoretical, real data should be collected to allow better model calibration.

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Firstly, we would like to thank all the Graphab team of the Thema laboratory who followed this work for more than a year and in particular Gilles Vuidel who helped us on the height's integration issue in Graphab. Furthermore, we would like to thank Engie Aire Nouvelle for funding this work in a partnership with MNHN. The authors declare no conflict of interest.

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Table 1: Resistance values for each land use type according to resistance gradations. *In resistance gradation 1 and 2, the resistance increased respectively linearly and exponentially with building's height. Thus, there were no difference between the two gradations for ground level structures i.e., water streams, green spaces and the non-vegetated open spaces.*

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Table 3: Global connectivity rate of change measured by the probability of connectivity (PC) including or excluding green roofs for the two resistance gradations and the three groups of species according to their dispersion capacity. (A): a_i is the surface of the patch i ; (B) :the area of all patches set to 1.

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Figure 4: Potential gain in probability of connectivity (PC) from greening new roofs according to their area (m^2), the dispersion capacities of the species, the resistance gradation. R and P-value corresponding to the Spearman correlation test.

Figure 5: potential gain in probability of connectivity (PC) from greening new roofs according to their median heights, the species' dispersion capacities and the resistance gradations (A) and Spearman's correlation, and p -value (B). The graph is here centered on PC values between 0 and 1 to make the graph more readable. 5 values exceed 1%, depending on distances, always in the case of roofs between 0 and 20 meters high, i.e. Land use code 30 and 31).

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Appendix A: Zero values proportion for the BC (betweenness centrality) and F (flux) index according to the type of habitat patches, connectivity metrics, links calculation methods and dispersion capacities

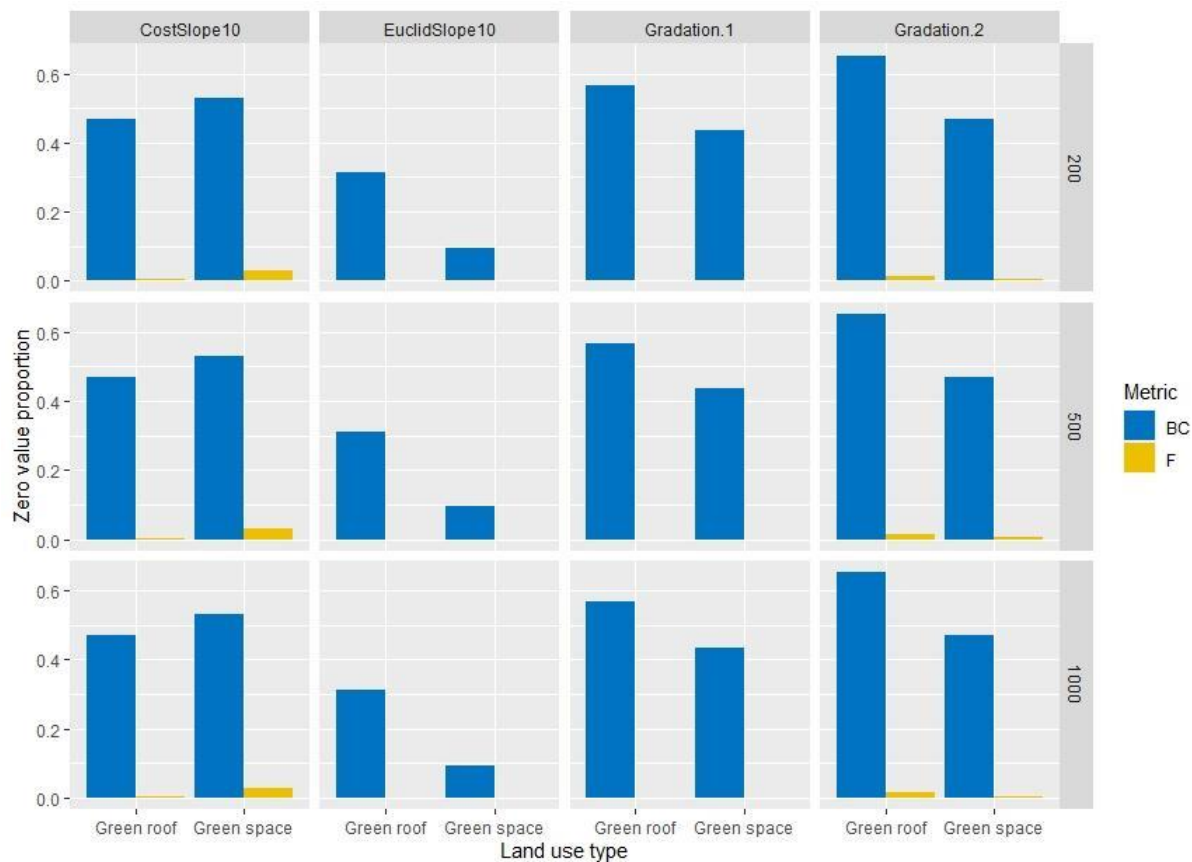
Appendix B: Zero values proportion for the BC (betweenness centrality) and F (flux) index, as a function of green roof height according to surface type, connectivity index, links calculation methods and dispersion capacities

Appendix C: Potential gain in probability of connectivity (PC) from greening new roofs

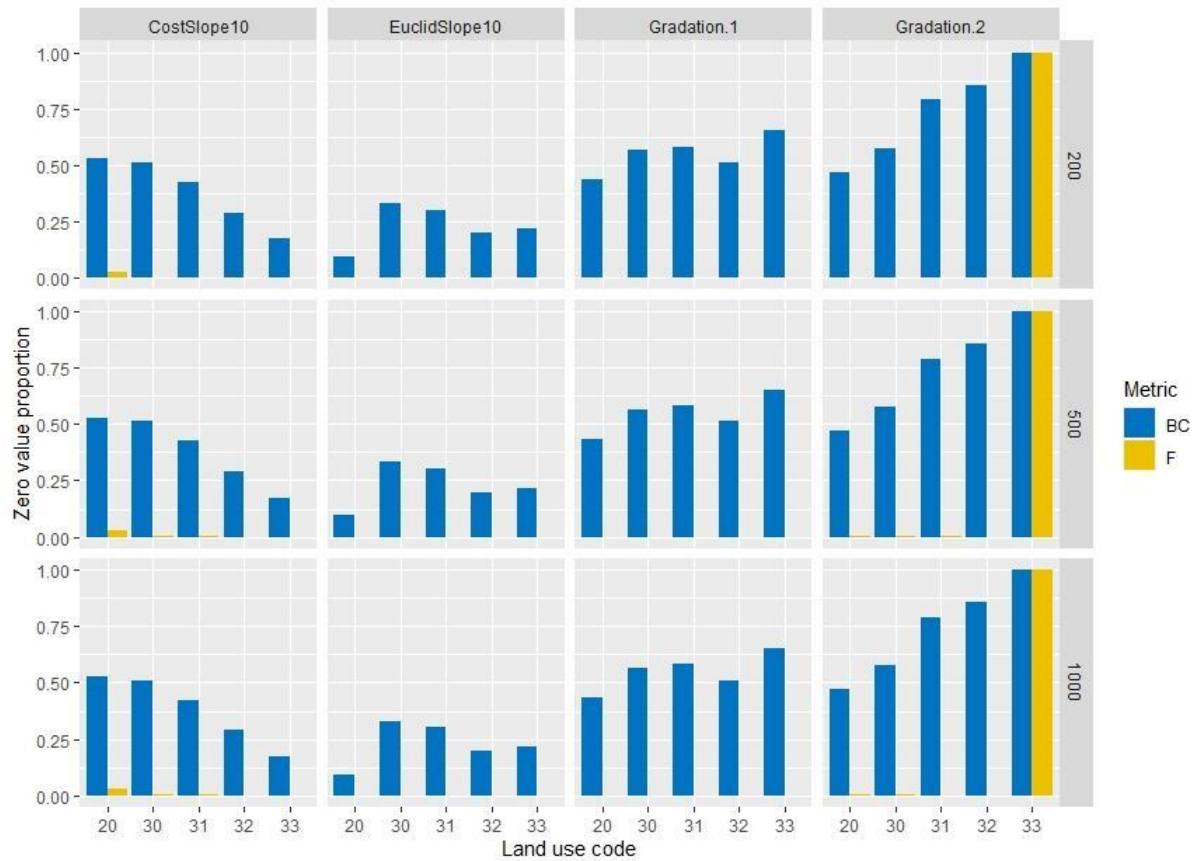
Appendix D: Zoom on EuclidSlope10 links calculation method. Comparison of the F (flux) (**A**) index and the BC (betweenness centrality) (**B**) index between green roofs and ground green spaces for the three types of dispersion capacity.

Appendices:

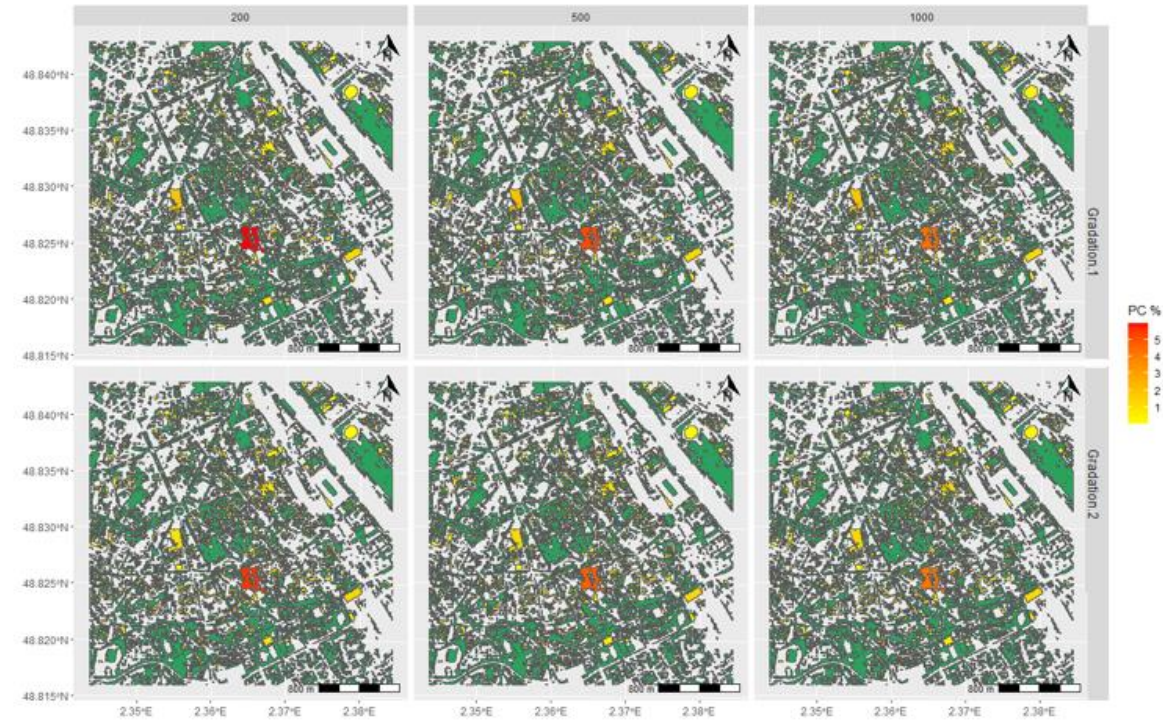
Appendix A: Zero values proportion for the BC (betweenness centrality) and F (flux) index according to the type of habitat patches, connectivity metrics, links calculation methods and dispersion capacities



Appendix B: Zero values proportion for the BC (betweenness centrality) and F (flux) index, as a function of green roof height according to surface type, connectivity index, links calculation methods and dispersion capacities



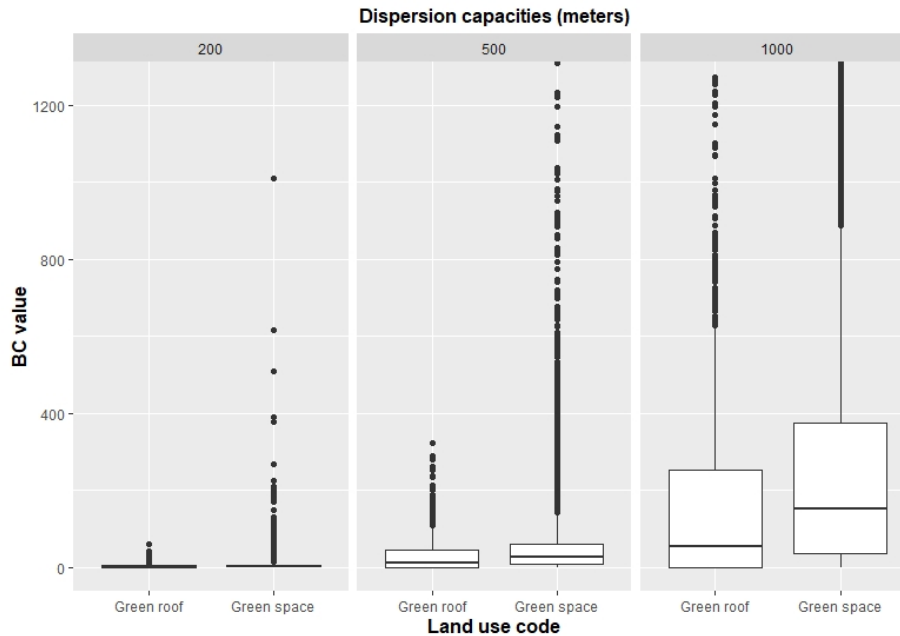
Appendix C: Potential gain in probability of connectivity (PC) from greening new roofs



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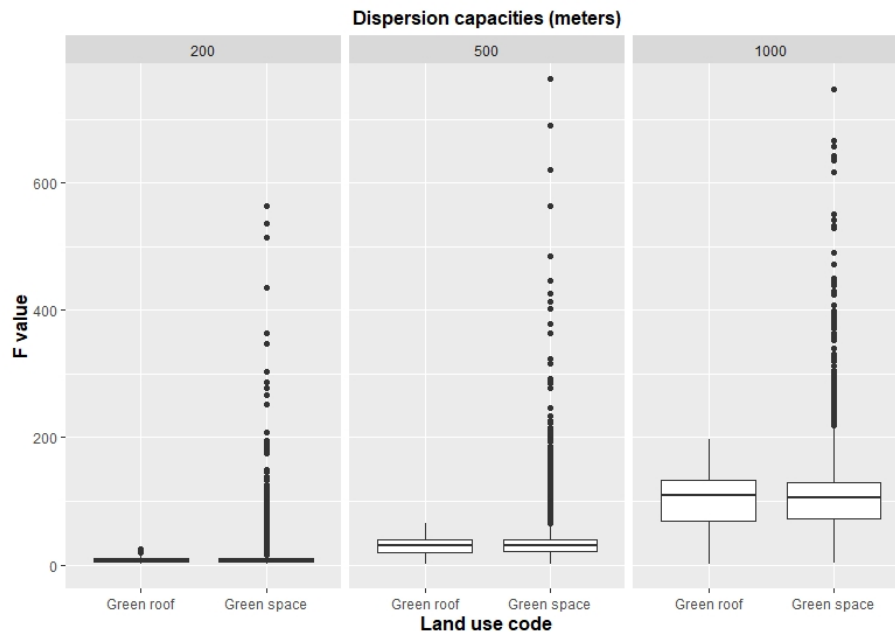
642 **Appendix D:** Zoom on EuclidSlope10 links calculation method. Comparison of the F (flux) **(A)** index and
 643 the BC (betweenness centrality) **(B)** index between green roofs and ground green spaces for the three
 644 types of dispersion capacity.

A



645

B



646

647 **Appendix E:** Comparison of the BC (betweenness centrality) values (A) and the F (flux) values according
 648 to the height of the green roof. Only 90% of the positive values were represented (quantile from 5 to
 649 95). **30:** green roofs > 0-10 m; **31:** green roofs > 10-20 m; **32:** green roofs > 20-30 m; **33:** green roofs > 30 m.

