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

Tanguy Louis-Lucas, Céline Clauzel, Flavie Mayrand, Philippe Clergeau, Nathalie Machon

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1 **Title:** Role of green roofs in urban connectivity, an exploratory approach using graph theory in the city  
 2 of Paris, France.

3 **Authors:** \*Tanguy LOUIS-LUCAS<sup>1</sup> (tanguy.louis-lucas1@mnhn.fr), Céline CLAUZEL<sup>2</sup> (celine.clauzel@u-  
 4 paris.fr), Flavie MAYRAND<sup>1</sup> (flavie.mayrand@mnhn.fr), Philippe CLERGEAU<sup>1</sup>  
 5 (philippe.clergeau@mnhn.fr) & Nathalie MACHON<sup>1</sup> (nathalie.machon@mnhn.fr)

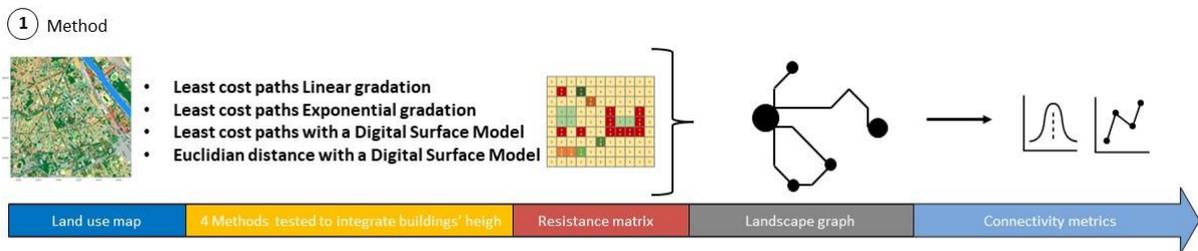
6 1: Centre d'Ecologie et des sciences de la conservation (CESCO), Muséum national d'Histoire naturelle,  
 7 Centre National de la Recherche Scientifique, Sorbonne Université, CP 135, 57 rue Cuvier 75005 Paris,  
 8 France.

9 2: Université Paris Cité, UMR CNRS 7533 LADYSS, Paris

10 \*Corresponding author: [tanguy.louis-lucas1@mnhn.fr](mailto:tanguy.louis-lucas1@mnhn.fr)

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

12



13

14 **Abstract**

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

31

32 **1. Introduction**

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

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

53 Concerning services to biodiversity, they offer urban species resources and habitats (Madre et al.,  
54 2013; Madre et al., 2014; Dusza, 2020) and are thus critical for biodiversity conservation (Williams et  
55 al., 2014; Lepczyk et al., 2017; Mayrand and Clergeau, 2018). Nevertheless, their contribution to the

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

63 Comparing biodiversity on green roofs and on ground green spaces revealed that the height of roofs  
64 generally affected their hosting capacity negatively, resulting in a decrease of bee number and species  
65 richness (Braaker et al. (2014, 2017) or Tonietto et al. (2011)). The negative influence of green roofs'  
66 height was also established on the richness, abundance, and composition on a variety of other taxa  
67 (Pearce and Walters, 2012; Madre et al., 2013; MacIvor, 2016; Dromgold et al., 2020; Mills and Rott,  
68 2020). Furthermore, Braaker et al. (2017), which is one of the only studies to analyzing the role of  
69 connectivity on species communities on roofs, showed that the community composition of highly  
70 mobile arthropods (bees, weevils) is directly influenced by structural connectivity (edge density,  
71 average Euclidean distance to the nearest habitat). In addition, they showed that the similarity of  
72 community compositions on roofs and on ground green spaces suggested vertical movements  
73 between these habitats.

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

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

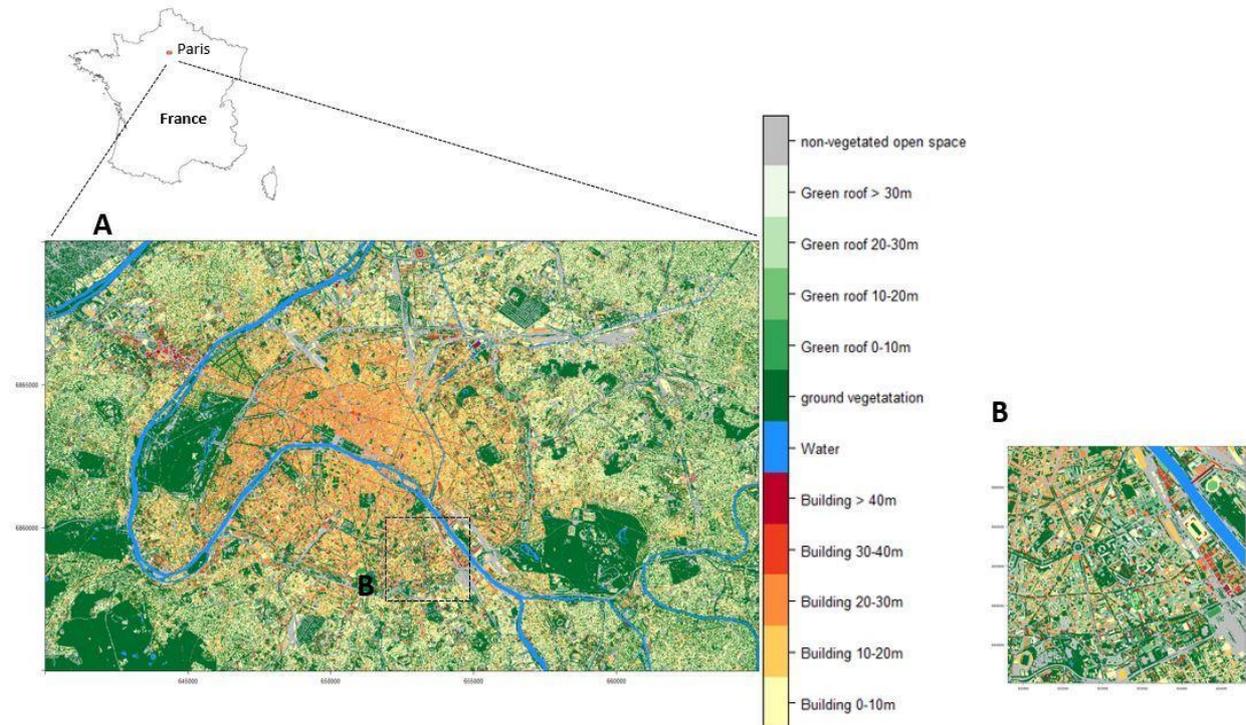
90

## 91 **2. Method**

### 92 **2.1. Study area**

93 Our study was carried out in the Paris region in France (Figure 1A). The study area covers 375 km<sup>2</sup>,  
94 from the cities of Saint-Denis in the north (48° 92' 77" N, 2° 35' 70" E), Cachan in the south (48° 79' 33"  
95 N, 2° 32' 08" E), Rueil-Malmaison in the west (48° 86' 24" N, 2° 18' 21" E) and Neuilly-sur-Marne in the  
96 east (48° 85' 24" N, 2° 52' 29" E). To address hypothesis n°4, a 3km square sample was selected (Figure  
97 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.



101

102

## 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

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

123 Three species groups with different dispersion capacities were considered, as in Serret et al. (2014):  
124 200 meters for low-mobility species such as barochorous plant or some solitary bees like *Chelostoma*  
125 *florisomme* or *Osmia bicornis* (Hofmann et al., 2020), 500 meters for medium-mobility species such as  
126 entomogamous plants or in a number of butterfly species like *Polyommatus icarus* and finally 1000  
127 meters for highly mobile species such as anemogamous species or some wild bees like *Chelostoma*  
128 *rapunculi* (Zurbuchen et al., 2010).

129

### 130 **2.3. Ecological networks modeling by integrating buildings' height**

131 From this land use map, the ecological networks for the three groups of flying organisms (animals or  
132 plants) were modeled based on landscape graphs using Graphab 2.8 software (Foltête, 2021). A  
133 landscape graph consists of habitat patches represented by points (nodes) and connected or not by  
134 links indicating a functional connection, i.e. a flow between two patches (Urban et al., 2009). In our  
135 study, habitat patches were defined as a set of adjacent vegetation pixels with an area of at least 100  
136 m<sup>2</sup> to reduce calculation time. Links were defined in planar topology and following four different  
137 methods to integrate building height in the calculation. Following the literature that showed a negative  
138 effect of height on biodiversity, the four methods were based on the same principle: assigning an  
139 increasing resistance according to building height.

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

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

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

163 *Costslope10*, the costs of land use types were weighted according to slope intensity. In *Euclidslope10*, the cost of each pixel  
 164 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

165

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

#### 170 **2.4. Connectivity metrics and data analysis**

##### 171 *2.4.1. Contribution of green roofs to global connectivity (metropole scale)*

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

$$179 \quad PC = \frac{\sum_{i=1}^n \sum_{j=1}^n a_i \times a_j \times p_{ij}^*}{A^2}$$

180 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  
 181 study area.  $P_{ij}$  represents the probability that  $i$  and  $j$  are connected by a link.  $P_{ij}$  can be calculated as  
 182 follows:

$$183 \quad p_{ij} = e^{-\alpha d_{ij}}$$

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

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

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

#### 190 2.4.2. Contribution of green roofs to local connectivity (patch scale) and effect of buildings' height

191 To understand the type of contribution of green roofs to local connectivity and to compare it with  
192 green spaces, we calculated two local metrics on the graph modeling the ecological network with green  
193 roofs, using the four links calculation's methods. The Betweenness Centrality (BC) (Bodin & Saura,  
194 2010) highlights the patches with a strategic position in the network. This metric is the sum of the  
195 shortest paths between each pair of patches weighted by their interaction probability:

$$196 \quad BC_i = \sum_j \sum_k a_j^\beta \times a_k^\beta \times e^{-\alpha d_{jk}}$$

197

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

$$202 \quad F_i = \sum_{j=1}^n a_j^\beta \times e^{-\alpha d_{jk}}$$

203

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

#### 207 2.4.3. Prospective analysis: effect of greening new roofs on connectivity

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

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

### 217 3. Results

218 The resulting land use map included a total of 41,065 habitat patches with a median area of 4,400 m<sup>2</sup>.  
219 95% of those patches were ground green spaces and represented 99% of the vegetated area (in m<sup>2</sup>)  
220 (Table 2).

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

Code	Land use	Mean Area (m <sup>2</sup> )	Sd Area (m <sup>2</sup> )	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

223

### 224 **3.1. Contribution of existing green roofs to global connectivity**

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

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

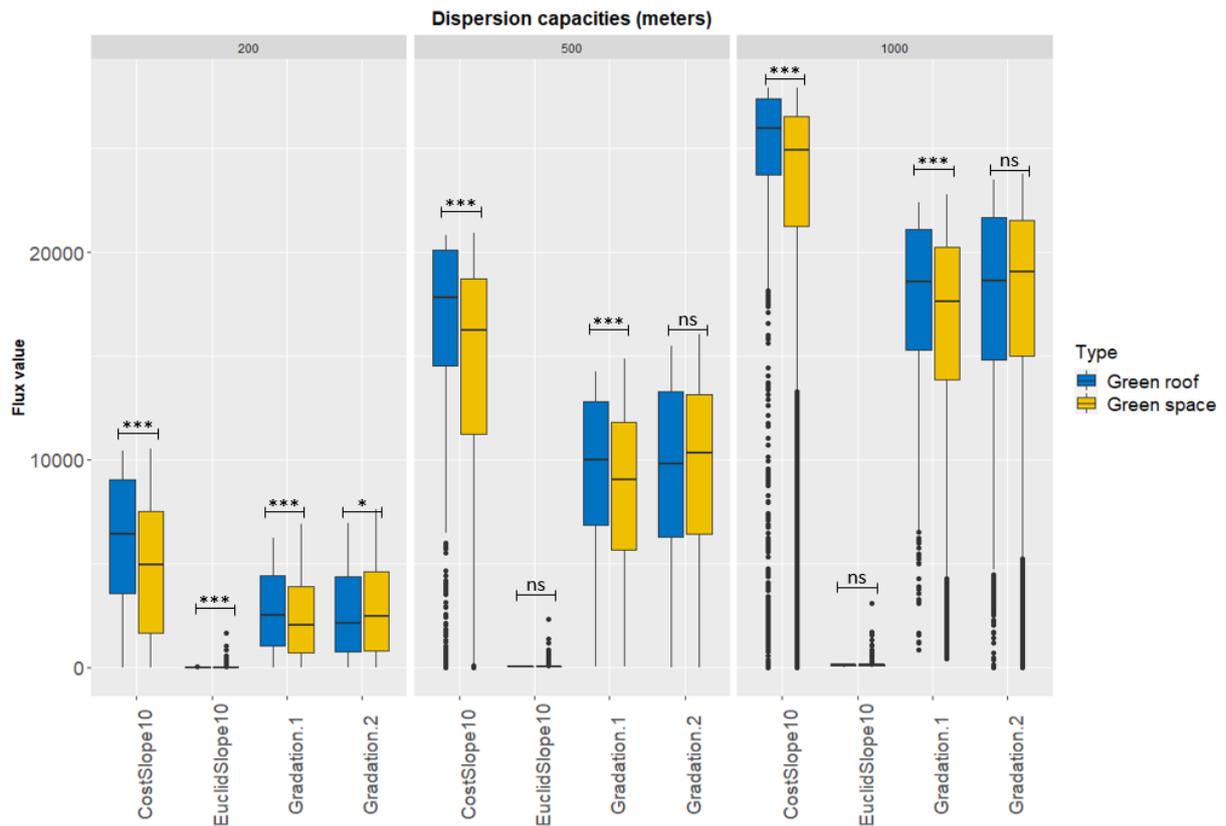
Distances	with/without green roof – gradation 1		with/without green roof – gradation 2	
	$a_i$ =area (A)	$a_i$ =1 (B)	$a_i$ =area (A)	$a_i$ =1 (B)
200	1.87%	12.95%	1.49%	10.44%
500	2.46%	11.75%	2.07%	10.15%
1000	2.69%	10.92%	2.35%	9.86%

234

### 235 **3.2. Type of contribution to connectivity of green roofs vs. ground green spaces**

236 The distribution of F and BC values for green roofs and ground spaces were compared for each of the  
 237 four link calculation methods (Figure 2). CostSlope10 had the highest values for the two metrics.  
 238 Gradations 1 and 2 had slightly smaller (almost half as much) and relatively close values. On the other  
 239 hand, EuclidSlope10 had the lowest values for both metrics. With gradation 1 (linear) and CostSlope10,  
 240 the average F values were higher for green roofs than for ground green spaces for all species groups.  
 241 With gradation 2 (exponential) and EuclidSlope10, the average F values of ground green spaces were  
 242 always higher, but the difference was not significant. With gradation 2, ground green spaces have  
 243 higher values of 2% for all dispersion distances. Conversely, for EuclidSlope10, the ratio decreased from  
 244 +11% for 200 m to +1% for 1000 m.

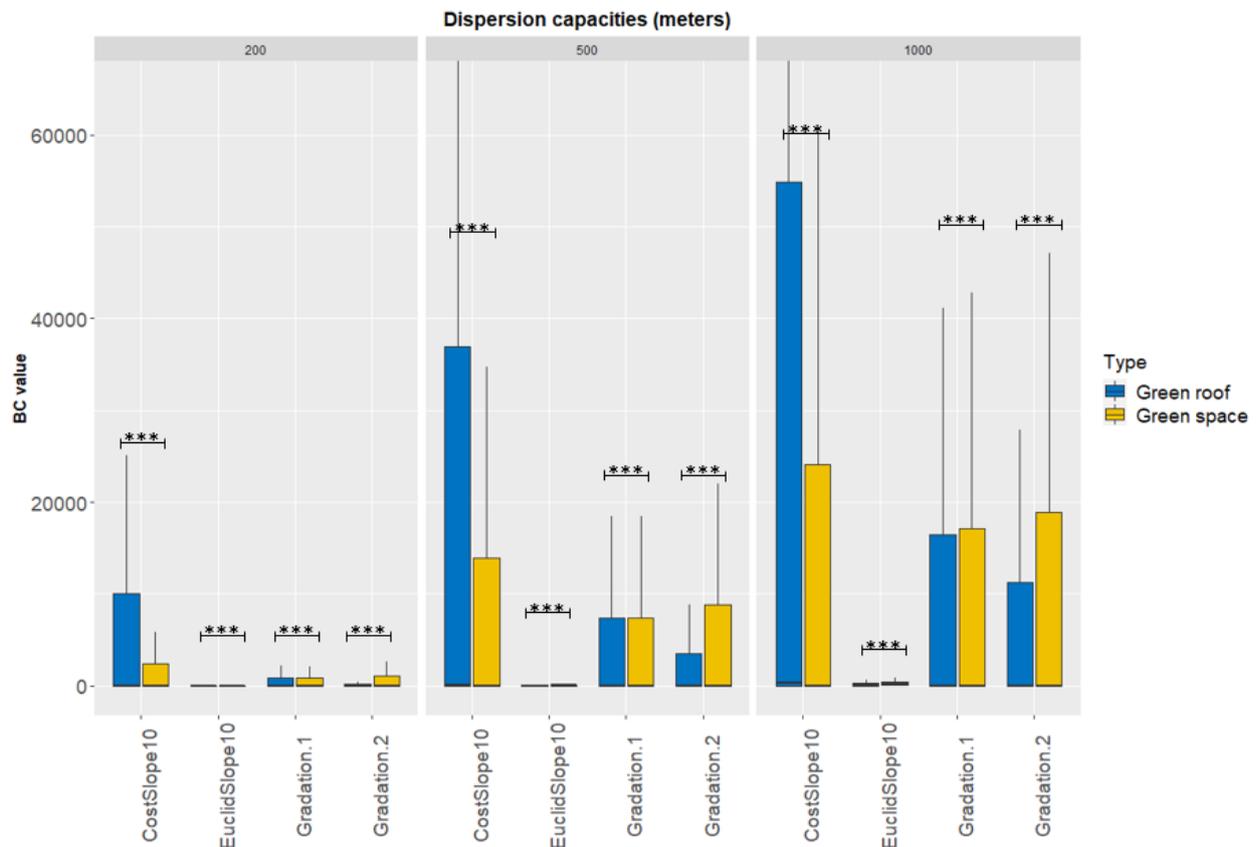
245 **Figure 2:** Comparison of the Flux (F) values between green roofs and ground green spaces for the four  
 246 resistance gradations and the three dispersion capacities. Stars represent significance levels from  
 247 Wilcoxon's test.



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.



261

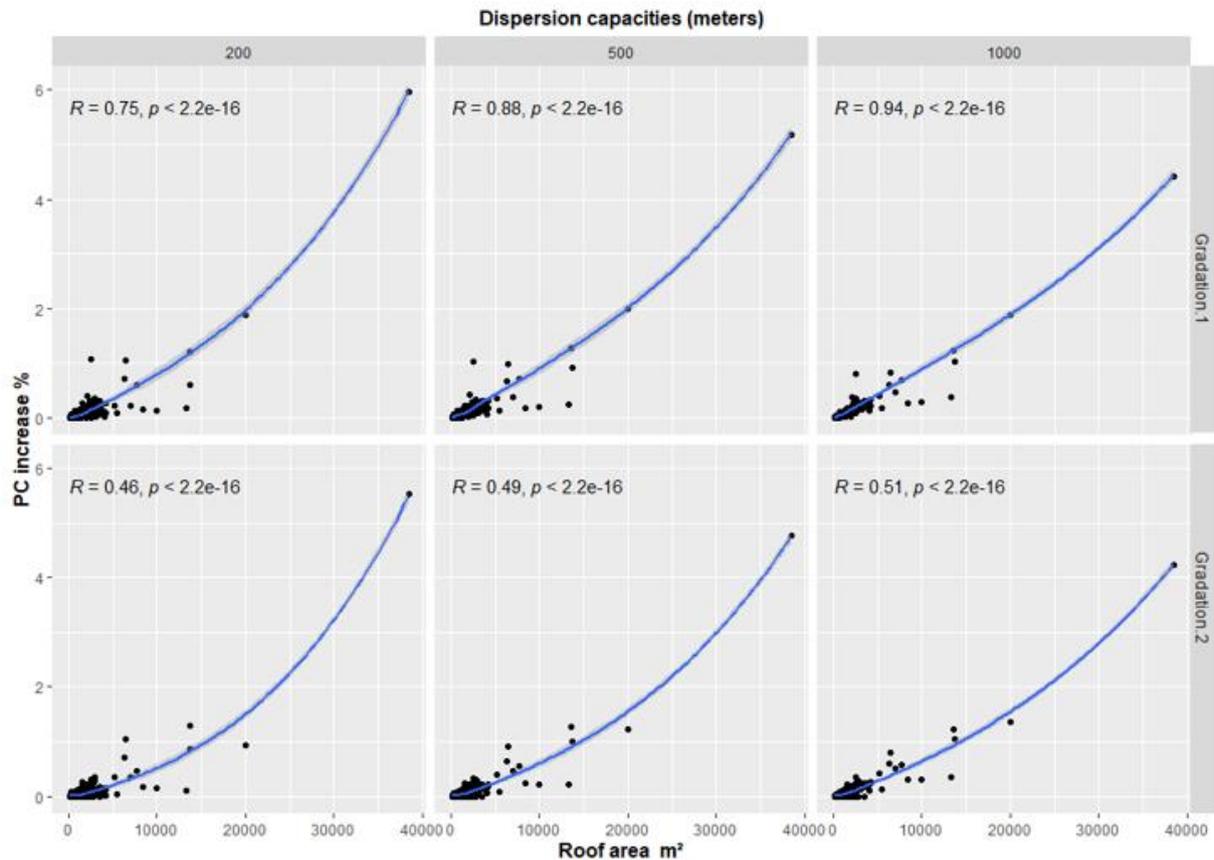
262 Many green roofs had a zero BC value, meaning they were not central in the network (Appendix A):  
 263 31% with EuclidSlope10, 47% with CostSlope10, 56% with gradation 1 and 65% with gradation 2. As  
 264 comparison, the proportion of zero values was lower for ground green spaces except with CostSlope10  
 265 (53%). Concerning F values, none of the green roofs had a zero value with gradation 1 and  
 266 EuclidSlope10, while 2% of the green roofs were completely isolated from the network ( $F = 0$ ) with  
 267 gradation 2 and less than 1% with CostSlope10. As comparison, none of the ground green spaces was  
 268 disconnected from the network with gradation 1 and EuclidSlope10 (whatever the dispersion  
 269 capacities), less than 2% with gradation 2 and 3% with CostSlope10. This suggested that green roofs  
 270 contributed more to connectivity in terms of dispersion flows through connections with other roofs  
 271 and green spaces than in terms of centrality.

### 272 **3.3. Contribution of new potential green roofs on connectivity**

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

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

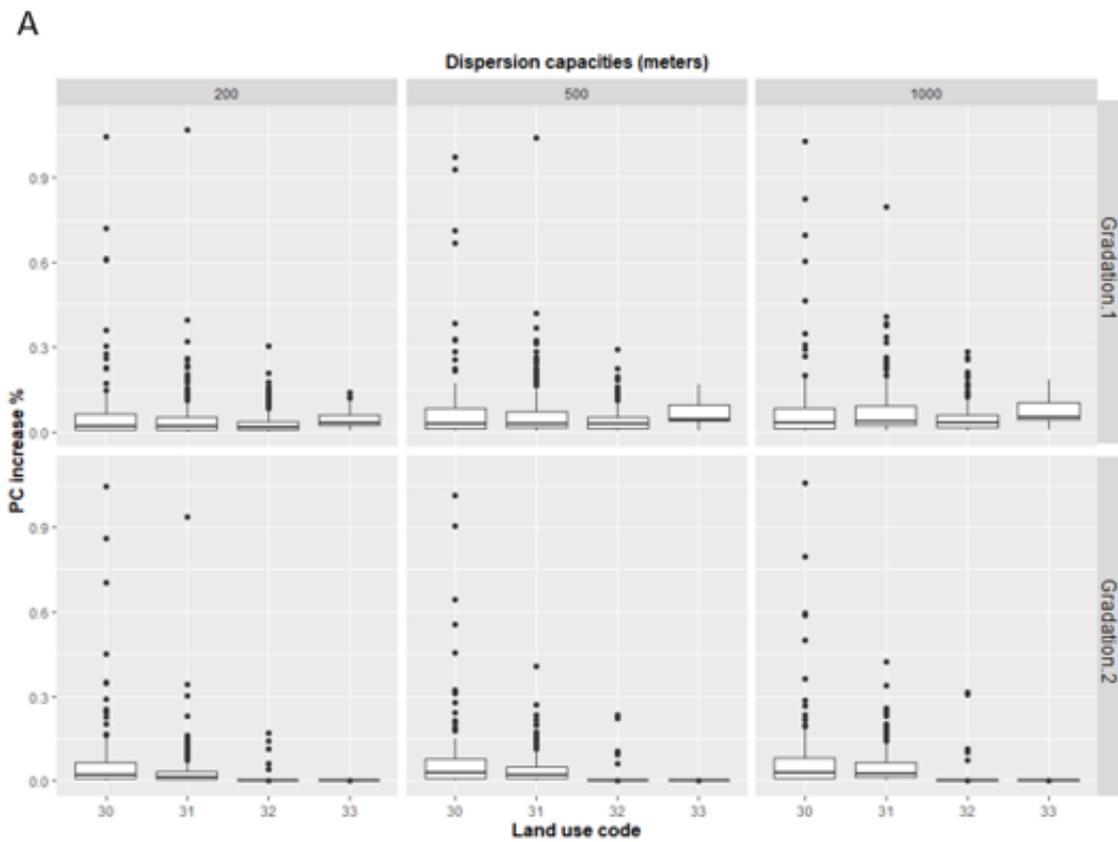
285 **Figure 4:** Potential gain in probability of connectivity (PC) from greening new roofs according to their  
 286 area (m<sup>2</sup>), the dispersion capacities of species, the resistance gradations 1 or 2. R and P-value  
 287 corresponding to the Spearman correlation test.



288  
 289 The gain in probability of connectivity (PC) provided by new green roofs was partly explained by their  
 290 area as shown in Figure 5. The two parameters were strongly correlated, especially in gradation 1 (from  
 291 R=0.75 to 0.94).

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

296 **Figure 5:** Potential gains in probability of connectivity (PC) from greening new roofs according to their  
 297 height, the species dispersion capacities and the resistance gradations (A), associated to Spearman's  
 298 correlation, and p-value (B). The graph is here centered on PC values between 0 and 1 to make it more readable.  
 299 5 values exceed 1%, all for roofs between 0 and 20 meters high, i.e., Land use codes 30 and 31). **30:** green roofs >  
 300 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

301

302

#### 303 **4. Discussion**

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

##### 306 **4.1. Green roofs contribute to connectivity but differently from ground green spaces**

307 At a global scale, our results suggest that green roofs contributed significantly to landscape  
308 connectivity. Thus, despite their small cumulative area compared to ground green spaces (less than  
309 1% of the total vegetated area) their contribution should not be minimized. The highest impact of  
310 green roofs on connectivity when PC was calculated without 'area' suggests that their contribution is  
311 more linked to network topology (i.e., connectivity *per se*) than to habitat amount. Surprisingly, while  
312 the PC gain increases with increasing dispersion capability when patch capacity is equal to area (i.e.,  $a_i$   
313 equal to the area of the patch  $i$ ), the PC gain is less strong as the distance increases (13% for 200 m to  
314 11% for 1000 m with gradation 1, Table 3) when the area of patches is considered as identical ( $a_i=1$ ).

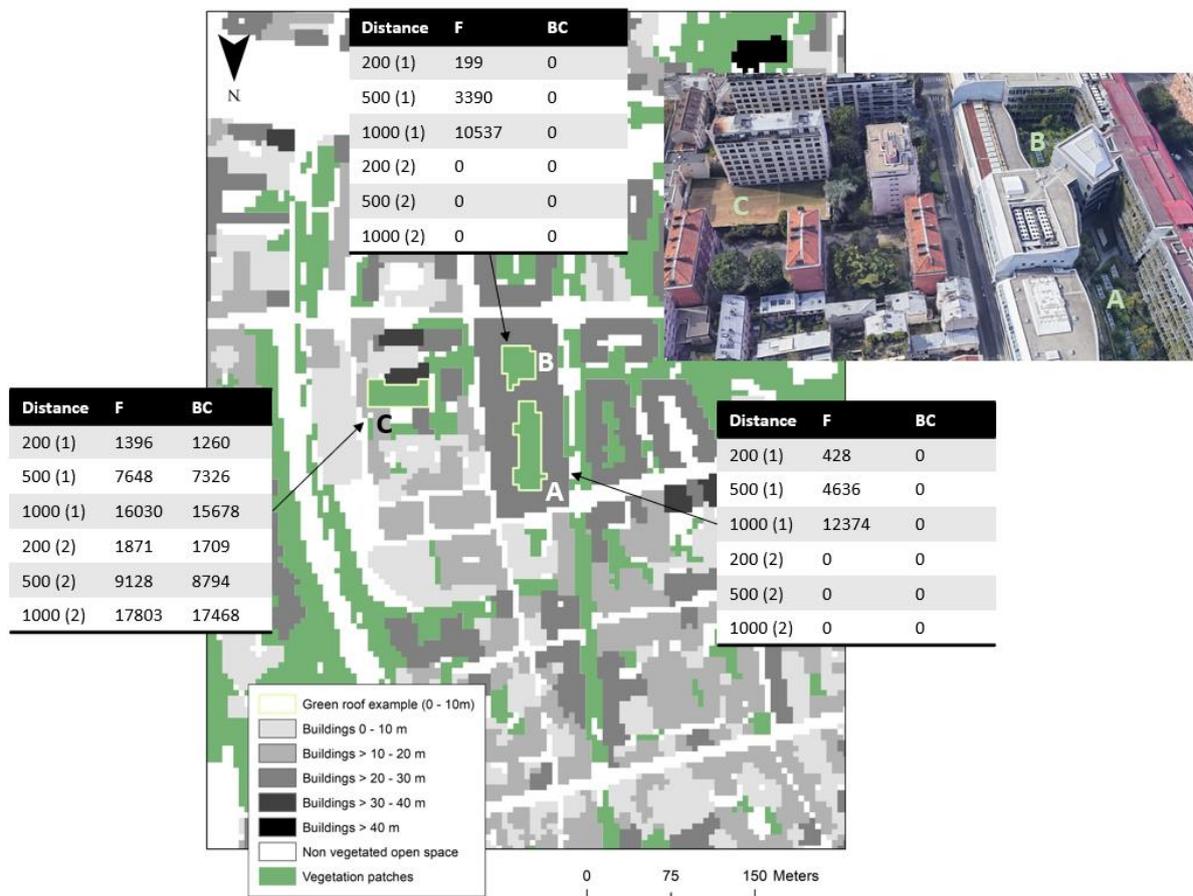
315 At the patch scale, green roofs often have higher Flux values (Figure 2) and lower BC values (Figure 3)  
316 than ground green spaces. This suggests that they have more of a role in terms of dispersal flows than  
317 as connectors between habitats, especially for relatively and highly mobile species.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

#### 320 **4.2. Height and building configuration strongly affect connectivity**

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

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

337



338

339

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

### 347 **4.3. Contributions and perspectives for urban connectivity evaluation**

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

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

368 Since our approach is exploratory, we made some unavoidable simplifying choices. First, we choose a  
369 resolution of 5m for the land use map. This resolution was determined after several tests to find the  
370 best compromise between accuracy and calculation time. As the minimum size of roofs is 100m<sup>2</sup>, a  
371 resolution of 25m<sup>2</sup> seemed sufficiently precise to capture these elements, as well as the other urban  
372 landscape elements such as roads or the shape of building (Figure 6). If this resolution seems sufficient  
373 for the metropolitan scale, it would be interesting to test a finer resolution for local analyses, especially  
374 since the used data on vegetation are available at very high resolution (i.e. 0.50m).

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

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

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

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

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

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

## 405 **5. Conclusion**

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

411 The approach we developed should be continued and new methods to integrate building height should  
412 be tested. Integrating other variables would be also necessary to increase our models' accuracy. The  
413 design of methods for analyzing connectivity in 3D is a major challenge, as highlighted by Foltête et al,  
414 (2021). Moreover, as our approach is exploratory and theoretical, real data should be collected to allow  
415 better model calibration.

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## 421 **References**

- 422 APUR, Atelier Parisien d'Urbanisme. (2013). *Étude sur le potentiel de végétalisation des toitures*  
423 *terrasses à Paris* (p. 44). [https://www.apur.org/fr/nos-travaux/etude-potentiel-vegetalisation-](https://www.apur.org/fr/nos-travaux/etude-potentiel-vegetalisation-toitures-terrasses-paris)  
424 [toitures-terrasses-paris](https://www.apur.org/fr/nos-travaux/etude-potentiel-vegetalisation-toitures-terrasses-paris)
- 425 Aronson, M. F. J., Nilon, C. H., Lepczyk, C. A., Parker, T. S., Warren, P. S., Cilliers, S. S., Goddard, M. A.,  
426 Hahs, A. K., Herzog, C., Katti, M., La Sorte, F. A., Williams, N. S. G., & Zipperer, W. (2016).  
427 Hierarchical filters determine community assembly of urban species pools. *Ecology*, *97*(11),  
428 2952-2963. <https://doi.org/10.1002/ecy.1535>
- 429 Beninde, J., Veith, M., & Hochkirch, A. (2015). Biodiversity in cities needs space: A meta-analysis of  
430 factors determining intra-urban biodiversity variation. *Ecology Letters*, *18*(6), 581-592.  
431 <https://doi.org/10.1111/ele.12427>
- 432 Blank, L., Vasl, A., Schindler, B. Y., Kadas, G. J., & Blaustein, L. (2017). Horizontal and vertical island  
433 biogeography of arthropods on green roofs: A review. *Urban Ecosystems*, *20*(4), 911-917.  
434 <https://doi.org/10.1007/s11252-016-0639-9>
- 435 Bodin, Ö., & Saura, S. (2010). Ranking individual habitat patches as connectivity providers: Integrating  
436 network analysis and patch removal experiments. *Ecological Modelling*, *221*(19), 2393-2405.  
437 <https://doi.org/10.1016/j.ecolmodel.2010.06.017>
- 438 Braaker, S., Ghazoul, J., Obrist, M. K., & Moretti, M. (2014). Habitat connectivity shapes urban  
439 arthropod communities: The key role of green roofs. *Ecology*, *95*(4), 1010-1021.  
440 <https://doi.org/10.1890/13-0705.1>

- 441 Braaker, S., Obrist, M. K., Ghazoul, J., & Moretti, M. (2017). Habitat connectivity and local conditions  
442 shape taxonomic and functional diversity of arthropods on green roofs. *Journal of Animal*  
443 *Ecology*, 86(3), 521-531. <https://doi.org/10.1111/1365-2656.12648>
- 444 Casalegno, S., Anderson, K., Cox, D. T. C., Hancock, S., & Gaston, K. J. (2017). Ecological connectivity in  
445 the three-dimensional urban green volume using waveform airborne lidar. *Scientific Reports*,  
446 7(1), 45571. <https://doi.org/10.1038/srep45571>
- 447 Chen, C., Mao, L., Qiu, Y., Cui, J., & Wang, Y. (2020). Walls offer potential to improve urban  
448 biodiversity. *Scientific Reports*, 10(1), 9905. <https://doi.org/10.1038/s41598-020-66527-3>
- 449 Dromgold, J. R., Threlfall, C. G., Norton, B. A., & Williams, N. S. G. (2020). Green roof and ground-level  
450 invertebrate communities are similar and are driven by building height and landscape context.  
451 *Journal of Urban Ecology*, 6(1), juz024. <https://doi.org/10.1093/jue/juz024>
- 452 Dunnett, N., Nagase, A., & Hallam, A. (2008). The dynamics of planted and colonising species on a  
453 green roof over six growing seasons 2001–2006: Influence of substrate depth. *Urban*  
454 *Ecosystems*, 11(4), 373-384. <https://doi.org/10.1007/s11252-007-0042-7>
- 455 Dupras, J., Marull, J., Parcerisas, L., Coll, F., Gonzalez, A., Girard, M., & Tello, E. (2016). The impacts of  
456 urban sprawl on ecological connectivity in the Montreal Metropolitan Region. *Environmental*  
457 *Science & Policy*, 58, 61-73. <https://doi.org/10.1016/j.envsci.2016.01.005>
- 458 Dusza, Y., Barot, S., Kraepiel, Y., Lata, J.-C., Abbadie, L., & Raynaud, X. (2017). Multifunctionality is  
459 affected by interactions between green roof plant species, substrate depth, and substrate type.  
460 *Ecology and Evolution*, 7(7), 2357-2369. <https://doi.org/10.1002/ece3.2691>
- 461 Dusza, Y., Kraepiel, Y., Abbadie, L., Barot, S., Carmignac, D., Dajoz, I., Gendreau, E., Lata, J.-C.,  
462 Meriguet, J., Motard, E., & Raynaud, X. (2020). Plant-pollinator interactions on green roofs are  
463 mediated by substrate characteristics and plant community composition. *Acta Oecologica*, 105,  
464 103559. <https://doi.org/10.1016/j.actao.2020.103559>
- 465 Flégeau, M. (2020). *Formes urbaines et biodiversité—Un état des connaissances*.  
466 <http://www.urbanisme-puca.gouv.fr/formes-urbaines-et-biodiversite-un-etat-des-a2156.html>
- 467 Foltête, J.-C., Clauzel, C., & Vuidel, G. (2012). A software tool dedicated to the modelling of landscape  
468 networks. *Environmental Modelling & Software*, 38, 316-327.  
469 <https://doi.org/10.1016/j.envsoft.2012.07.002>
- 470 Foltête, J.-C., Girardet, X., & Clauzel, C. (2014). A methodological framework for the use of landscape  
471 graphs in land-use planning. *Landscape and Urban Planning*, 124, 140-150.  
472 <https://doi.org/10.1016/j.landurbplan.2013.12.012>
- 473 Foltête, J. C., Savary, P., Clauzel, C., Bourgeois, M., Girardet, X., Sahraoui, Y., Vuidel G. & Garnier, S.  
474 (2020). Coupling landscape graph modeling and biological data: a review. *Landscape Ecology*,  
475 35(5), 1035-1052. <https://doi.org/10.1007/s10980-020-00998-7>
- 476 Foltête, J.-C., Vuidel, G., Savary, P., Clauzel, C., Sahraoui, Y., Girardet, X., & Bourgeois, M. (2021).  
477 Graphab: An application for modeling and managing ecological habitat networks. *Software*  
478 *Impacts*, 8, 100065. <https://doi.org/10.1016/j.simpa.2021.100065>

- 479 Francis, L. F. M., & Jensen, M. B. (2017). Benefits of green roofs: A systematic review of the evidence  
480 for three ecosystem services. *Urban Forestry & Urban Greening*, 28, 167-176.  
481 <https://doi.org/10.1016/j.ufug.2017.10.015>
- 482 Hofmann, M. M., Fleischmann, A., & Renner, S. S. (2020). Foraging distances in six species of solitary  
483 bees with body lengths of 6 to 15 mm, inferred from individual tagging, suggest 150 m-rule-of-  
484 thumb for flower strip distances. *Journal of Hymenoptera Research*, 77, 105-117.  
485 <https://doi.org/10.3897/jhr.77.51182>
- 486 Jim, C. Y. (2012a). *Sustainable urban greening strategies for compact cities in developing and*  
487 *developed economies* | SpringerLink. 16, 741-761. <https://doi.org/10.1007/s11252-012-0268-x>
- 488 Jim, C. Y. (2012b). Effect of vegetation biomass structure on thermal performance of tropical green  
489 roof. *Landscape and Ecological Engineering*, 8(2), 173-187. [https://doi.org/10.1007/s11355-011-](https://doi.org/10.1007/s11355-011-0161-4)  
490 [0161-4](https://doi.org/10.1007/s11355-011-0161-4)
- 491 Joshi, M. Y., & Teller, J. (2021). Urban integration of green roofs: Current challenges and  
492 perspectives. *Sustainability*, 13(22), 12378. <https://doi.org/10.3390/su132212378>
- 493 Kalusová, V., Čeplová, N., & Lososová, Z. (2017). Which traits influence the frequency of plant species  
494 occurrence in urban habitat types? *Urban Ecosystems*, 20(1), 65-75.  
495 <https://doi.org/10.1007/s11252-016-0588-3>
- 496 Kyrö, K., Brenneisen, S., Kotze, D. J., Szallies, A., Gerner, M., & Lehvävirta, S. (2018). Local habitat  
497 characteristics have a stronger effect than the surrounding urban landscape on beetle  
498 communities on green roofs. *Urban Forestry & Urban Greening*, 29, 122-130.  
499 <https://doi.org/10.1016/j.ufug.2017.11.009>
- 500 Lepczyk, C. A., Aronson, M. F. J., Evans, K. L., Goddard, M. A., Lerman, S. B., & MacIvor, J. S. (2017).  
501 Biodiversity in the City: Fundamental Questions for Understanding the Ecology of Urban Green  
502 Spaces for Biodiversity Conservation. *BioScience*, 67(9), 799-807.  
503 <https://doi.org/10.1093/biosci/bix079>
- 504 Liang, H.-H., & Huang, K.-T. (2011). Study on rooftop outdoor thermal environment and slab  
505 insulation performance of grass planted roof. *International Journal of Physical Sciences*, 6(1), 65-  
506 73. <https://doi.org/10.5897/IJPS10.664>
- 507 Louis-Lucas, T., Mayrand, F., Clergeau, P., & Machon, N. (2021). Remote sensing for assessing  
508 vegetated roofs with a new replicable method in Paris, France. *Journal of Applied Remote*  
509 *Sensing*, 15(1), 014501.
- 510 Lundholm, J. T., & Williams, N. S. G. (2015). Effects of Vegetation on Green Roof Ecosystem Services.  
511 In R. K. Sutton (Éd.), *Green Roof Ecosystems* (Vol. 223, p. 211-232). Springer International  
512 Publishing. [https://doi.org/10.1007/978-3-319-14983-7\\_9](https://doi.org/10.1007/978-3-319-14983-7_9)
- 513 MacIvor, J. S. (2016). Building height matters: Nesting activity of bees and wasps on vegetated roofs.  
514 *Israel Journal of Ecology and Evolution*, 62(1-2), 88-96.  
515 <https://doi.org/10.1080/15659801.2015.1052635>

- 516 Madre, F., Vergnes, A., Machon, N., & Clergeau, P. (2013). A comparison of 3 types of green roof as  
517 habitats for arthropods. *Ecological Engineering*, 57, 109-117.  
518 <https://doi.org/10.1016/j.ecoleng.2013.04.029>
- 519 Madre, F., Vergnes, A., Machon, N., & Clergeau, P. (2014). Green roofs as habitats for wild plant  
520 species in urban landscapes: First insights from a large-scale sampling. *Landscape and Urban*  
521 *Planning*, 122, 100-107. <https://doi.org/10.1016/j.landurbplan.2013.11.012>
- 522 Mayrand, F., & Clergeau, P. (2018). Green Roofs and Green Walls for Biodiversity Conservation: A  
523 Contribution to Urban Connectivity? *Sustainability*, 10(4), 985.  
524 <https://doi.org/10.3390/su10040985>
- 525 McKinney, M. L. (2008). Effects of urbanization on species richness : A review of plants and animals.  
526 *Urban Ecosystems*, 11(2), 161-176. <https://doi.org/10.1007/s11252-007-0045-4>
- 527 Mills, W. P., & Rott, A. (2020). Vertical life: Impact of roof height on beetle diversity and abundance  
528 on wildflower green roofs. *Journal of Urban Ecology*, 6(1), juaa017.  
529 <https://doi.org/10.1093/jue/juaa017>
- 530 Mimet, A., Clauzel, C. et Foltête, J.-C. (2016). Locating wildlife crossings for multispecies connectivity  
531 across linear infrastructures. *Landscape Ecology*, 31(9), 1955-1973.  
532 <https://doi.org/10.1007/s10980-016-0373-y>
- 533 Morau, D., Tiana, R. H., Fanomezana, R. T., & Ludovic, A. A. (2014). Thermal Behavior of Green Roof in  
534 Reunion Island: Contribution Towards a Net Zero Building. *Energy Procedia*, 57, Dominique  
535 MORAU. <https://doi.org/10.1016/j.egypro.2014.10.055>
- 536 Muratet, A., Lorrillière, R., Clergeau, P., & Fontaine, C. (2013). Evaluation of landscape connectivity at  
537 community level using satellite-derived NDVI. *Landscape Ecology*, 28(1), 95-105.  
538 <https://doi.org/10.1007/s10980-012-9817-1>
- 539 Pearce, H., & Walters, C. L. (2012). Do Green Roofs Provide Habitat for Bats in Urban Areas? *Acta*  
540 *Chiropterologica*, 14(2), 469-478. <https://doi.org/10.3161/150811012X661774>
- 541 Penone, C., Machon, N., Julliard, R., & Le Viol, I. (2012). Do railway edges provide functional  
542 connectivity for plant communities in an urban context? *Biological Conservation*, 148(1), 126-  
543 133. <https://doi.org/10.1016/j.biocon.2012.01.041>
- 544 Peralta, G., Fenoglio, M. S., & Salvo, A. (2011). Physical barriers and corridors in urban habitats affect  
545 colonisation and parasitism rates of a specialist leaf miner. *Ecological Entomology*, 36(6), 673-  
546 679. <https://doi.org/10.1111/j.1365-2311.2011.01316.x>
- 547 Sahraoui, Y., Foltête, J.-C., & Clauzel, C. (2017). A multi-species approach for assessing the impact of  
548 land-cover changes on landscape connectivity. *Landscape Ecology*, 32(9), 1819-1835.  
549 <https://doi.org/10.1007/s10980-017-0551-6>
- 550 Saura, S., & Pascual-Hortal, L. (2007). A new habitat availability index to integrate connectivity in  
551 landscape conservation planning: Comparison with existing indices and application to a case  
552 study. *Landscape and Urban Planning*, 83(2-3), 91-103.  
553 <https://doi.org/10.1016/j.landurbplan.2007.03.005>

- 554 Saura, S., & Rubio, L. (2010). A common currency for the different ways in which patches and links can  
555 contribute to habitat availability and connectivity in the landscape. *Ecography*, 33, 19.  
556 <https://doi.org/10.1111/j.1600-0587.2009.05760.x>
- 557 Schleicher, A., Biedermann, R., & Kleyer, M. (2011). Dispersal traits determine plant response to  
558 habitat connectivity in an urban landscape. *Landscape Ecology*, 26(4), 529-540.  
559 <https://doi.org/10.1007/s10980-011-9579-1>
- 560 Serret, H., Raymond, R., Foltête, J.-C., Clergeau, P., Simon, L., & Machon, N. (2014). Potential  
561 contributions of green spaces at business sites to the ecological network in an urban  
562 agglomeration : The case of the Ile-de-France region, France. *Landscape and Urban Planning*,  
563 131, 27-35. <https://doi.org/10.1016/j.landurbplan.2014.07.003>
- 564 Tarabon, S., Calvet, C., Delbar, V., Dutoit, T., & Isselin-Nondedeu, F. (2020). Integrating a landscape  
565 connectivity approach into mitigation hierarchy planning by anticipating urban dynamics.  
566 *Landscape and Urban Planning*, 202, 103871.  
567 <https://doi.org/10.1016/j.landurbplan.2020.103871>
- 568 Tonietto, R., Fant, J., Ascher, J., Ellis, K., & Larkin, D. (2011). A comparison of bee communities of  
569 Chicago green roofs, parks and prairies. *Landscape and Urban Planning*, 103(1), 102-108.  
570 <https://doi.org/10.1016/j.landurbplan.2011.07.004>
- 571 Tratalos, J., Fuller, R. A., Warren, P. H., Davies, R. G., & Gaston, K. J. (2007). Urban form, biodiversity  
572 potential and ecosystem services. *Landscape and Urban Planning*, 83(4), 308-317.  
573 <https://doi.org/10.1016/j.landurbplan.2007.05.003>
- 574 Urban, D. L., Minor, E. S., Tremblay, E. A., & Schick, R. S. (2009). Graph models of habitat mosaics. *Ecology*  
575 *Letters*, 12(3), 260-273. <https://doi.org/10.1111/j.1461-0248.2008.01271.x>
- 576 Vergnes, A., Saux, E. L., & Clergeau, P. (2017). Preliminary data on low aerial plankton in a large city  
577 center, Paris. *Urban Forestry & Urban Greening*, 22, 36-40.  
578 <https://doi.org/10.1016/j.ufug.2017.01.012>
- 579 Vergnes, A., Viol, I. L., & Clergeau, P. (2012). Green corridors in urban landscapes affect the arthropod  
580 communities of domestic gardens. *Biological Conservation*, 145(1), 171-178.  
581 <https://doi.org/10.1016/j.biocon.2011.11.002>
- 582 Williams, N. S. G., Lundholm, J., & MacIvor, J. S. (2014). FORUM: Do green roofs help urban  
583 biodiversity conservation? *Journal of Applied Ecology*, 51(6), 1643-1649.  
584 <https://doi.org/10.1111/1365-2664.12333>
- 585 Zurbuchen, A., Landert, L., Klaiber, J., Müller, A., Hein, S., & Dorn, S. (2010). Maximum foraging ranges  
586 in solitary bees: Only few individuals have the capability to cover long foraging distances.  
587 *Biological Conservation*, 143(3), 669-676. <https://doi.org/10.1016/j.biocon.2009.12.003>

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589 **List of tables:**

590 **Table 1:** Resistance values for each land use type according to resistance gradations. *In resistance gradation*  
591 *1 and 2, the resistance increased respectively linearly and exponentially with building's height. Thus, there were no difference*  
592 *between the two gradations for ground level structures i.e., water streams, green spaces and the non-vegetated open spaces.*

593 **Table 2:** Statistical description of green roof and ground green space patches in the entire study area  
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595 **Table 3:** Global connectivity rate of change measured by the probability of connectivity (PC) including  
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597 to their dispersion capacity. (A):  $a_i$  is the surface of the patch  $i$ ; (B) :the area of all patches set to 1.

#### 598 **List of figures:**

599 **Figure 1:** Study area and the corresponding 5 meter-resolution land use map of the Paris region,  
600 France. **A** is the entire study area used to test hypotheses  $n^{\circ}1$  to  $n^{\circ}3$  and **B** is a 3km square sample to  
601 test hypothesis  $n^{\circ}4$ .

602 **Figure 2:** Comparison of the F (Flux) index between green roofs and ground green spaces for the two  
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604 from Wilcoxon's test.

605 **Figure 3:** Comparison the BC (Betweenness centrality) index between green roofs and ground green  
606 spaces. Only 90% of the values are represented (quantile from 5 to 95). Stars represent significance  
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608 **Figure 4:** Potential gain in probability of connectivity (PC) from greening new roofs according to their  
609 area ( $m^2$ ), the dispersion capacities of the species, the resistance gradation. R and P-value  
610 corresponding to the Spearman correlation test.

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612 median heights, the species' dispersion capacities and the resistance gradations (A) and Spearman's  
613 correlation, and  $p$ -value (B). The graph is here centered on PC values between 0 and 1 to make the graph more  
614 readable. 5 values exceed 1%, depending on distances, always in the case of roofs between 0 and 20 meters high,  
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616 **Figure 6:** Impact of buildings shapes on the contribution of green roofs to connectivity. Aerial image  
617 from google maps, 2021. A, B, C are three green roofs in eastern Paris. F (flux) and BC (betweenness centrality)  
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#### 619 **List of Appendices**

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

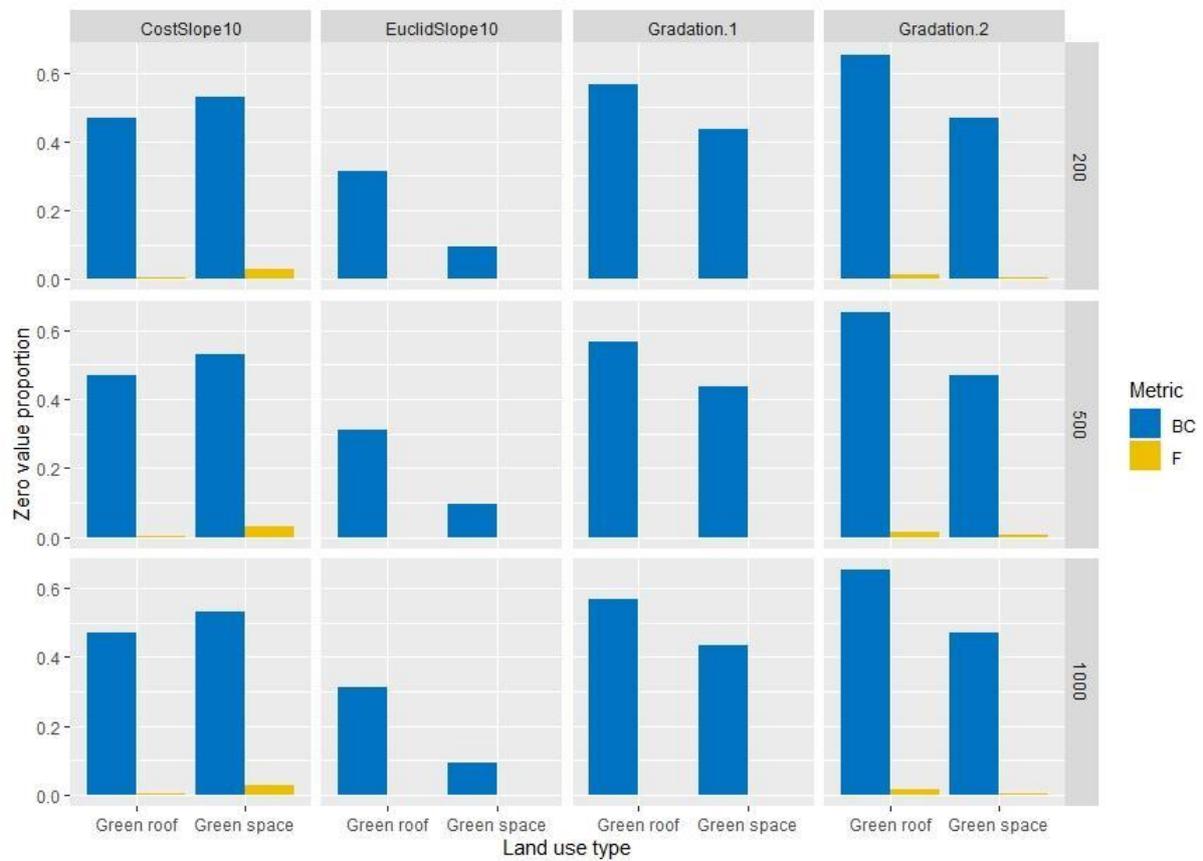
622 **Appendix B:** Zero values proportion for the BC (betweenness centrality) and F (flux) index, as a function  
623 of green roof height according to surface type, connectivity index, links calculation methods and  
624 dispersion capacities

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628 types of dispersion capacity.

629 **Appendices:**

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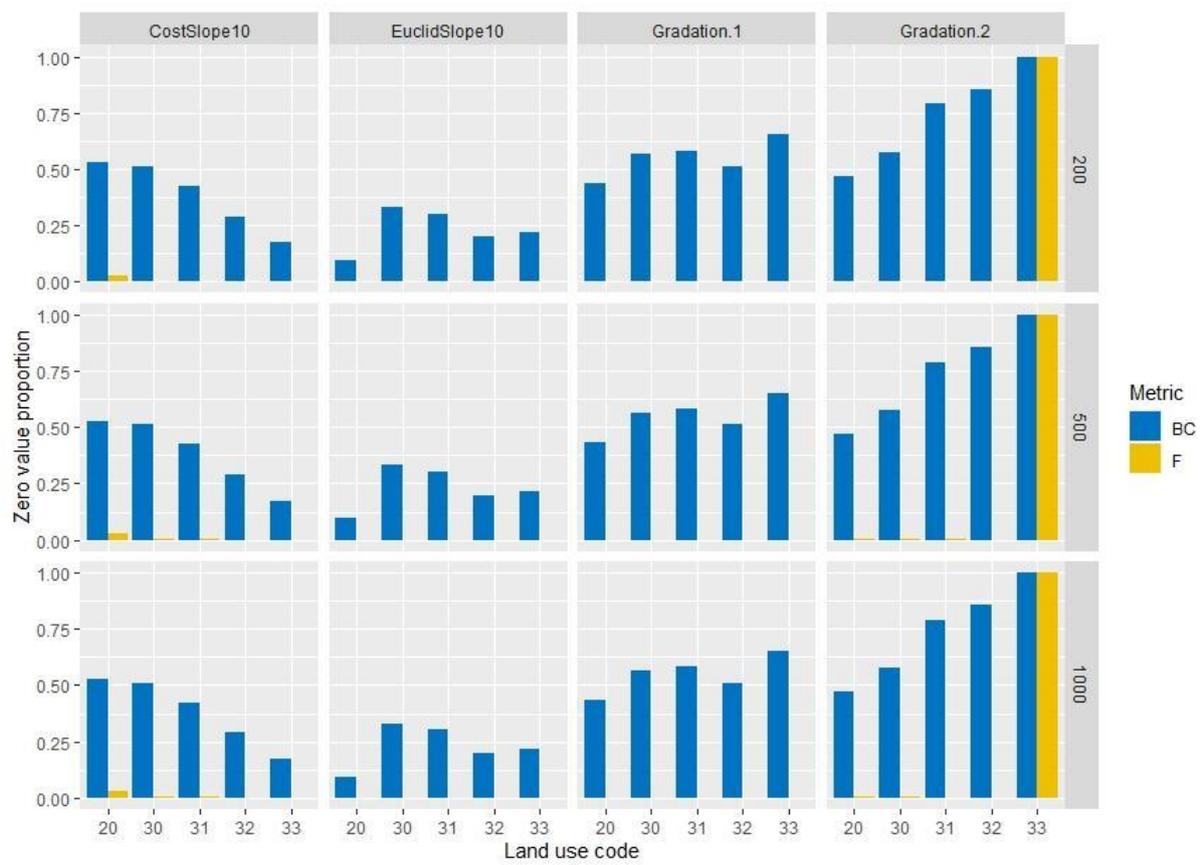


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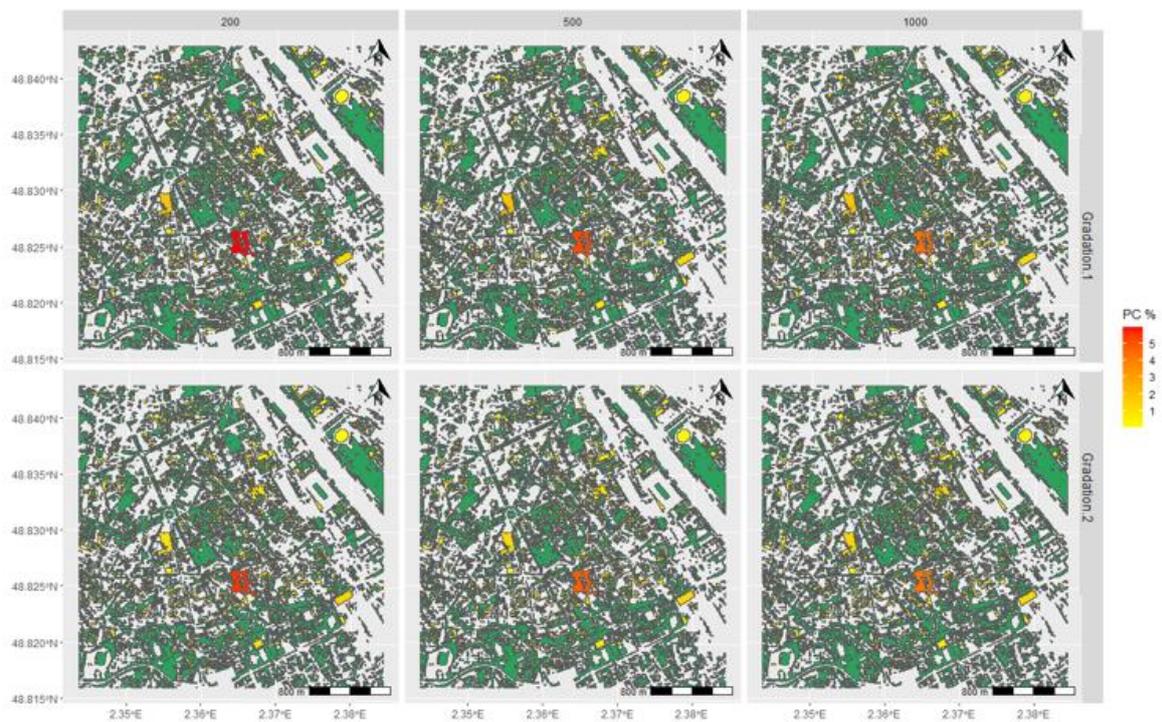
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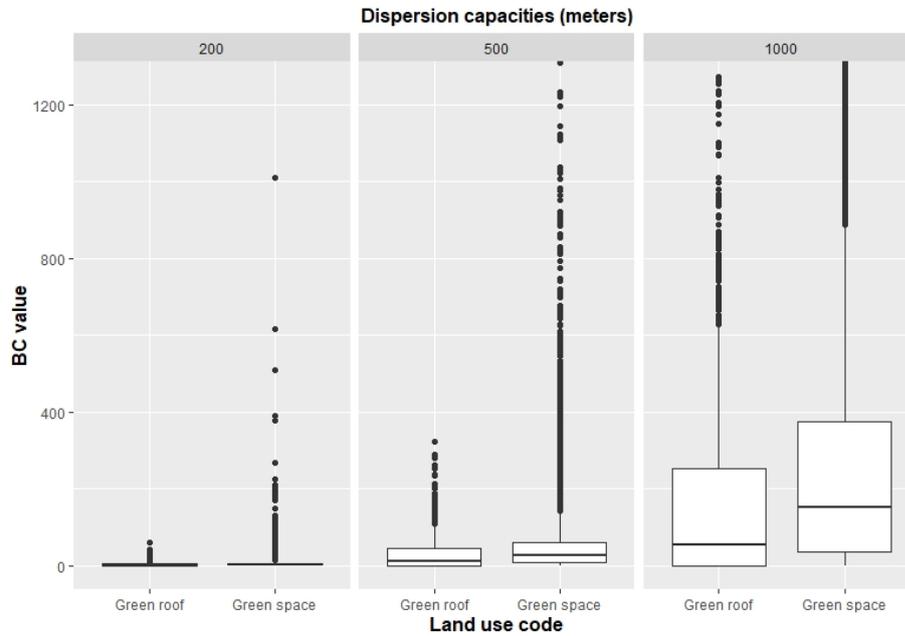


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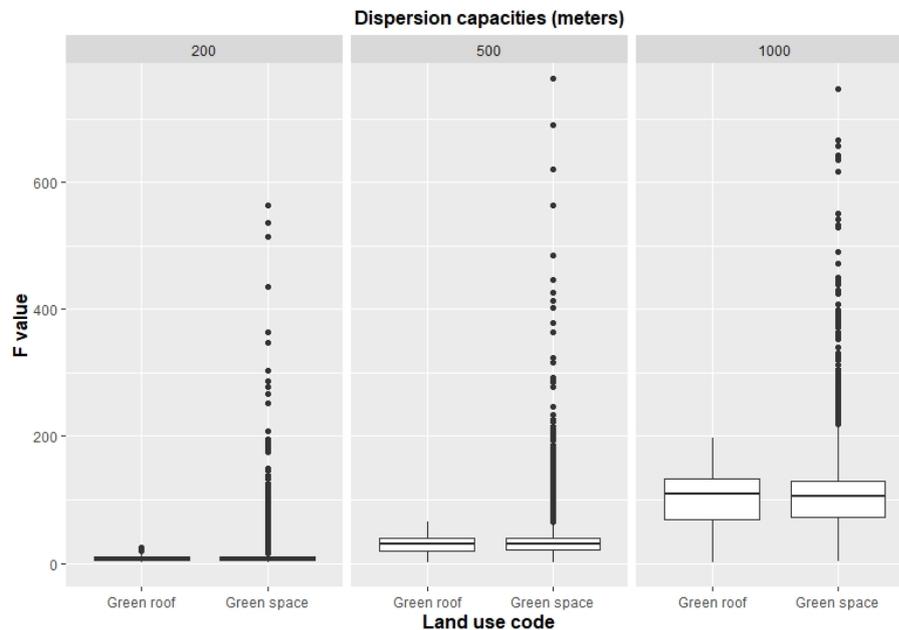
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643 the BC (betweenness centrality) (B) index between green roofs and ground green spaces for the three  
644 types of dispersion capacity.

A



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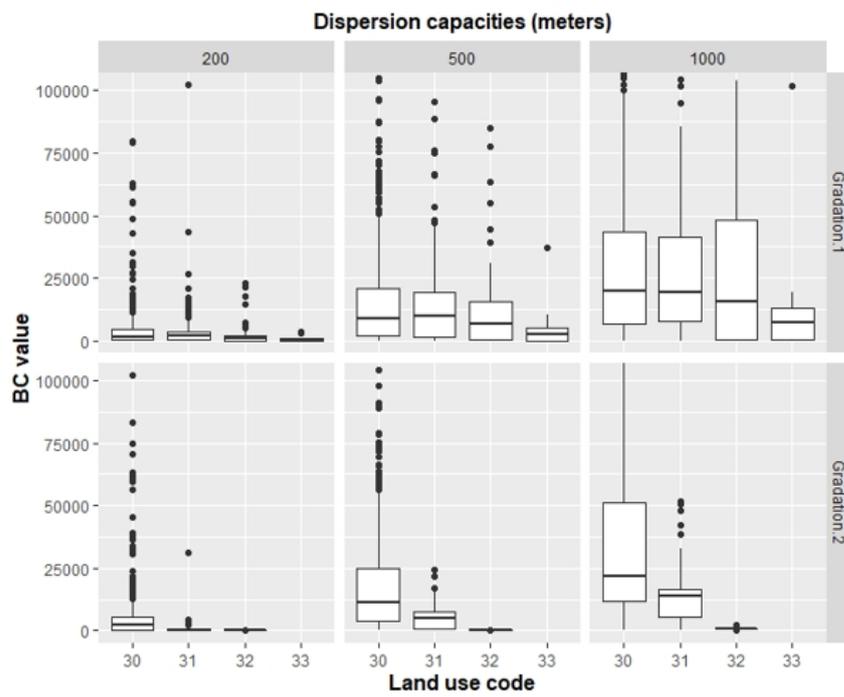
B



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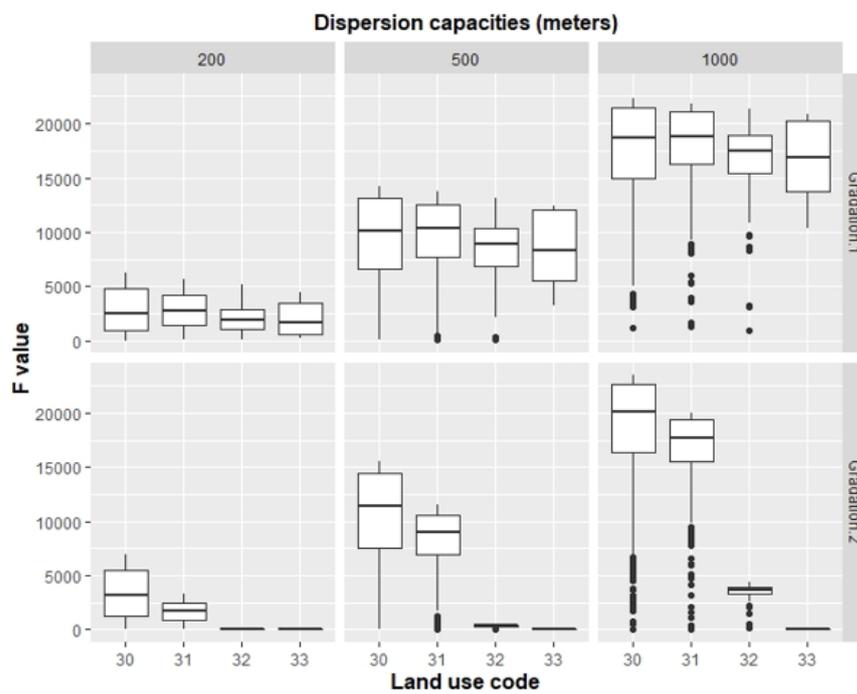
647 **Appendix E:** Comparison of the BC (betweenness centrality) values (A) and the F (flux) values according  
648 to the height of the green roof. Only 90% of the positive values were represented (quantile from 5 to  
649 95). **30:** green roofs > 0-10 m; **31:** green roofs > 10-20 m; **32:** green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

**A**



650

**B**



651