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

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1 **Title:** Role of green roofs in urban connectivity, an exploratory approach using graph theory in the city
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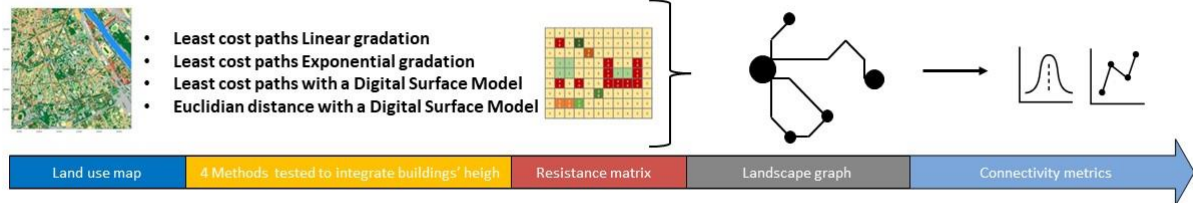
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11 **Graphical Abstract: What is the green roofs potential role in cities' ecological networks?**
 12

1 Method



2 Results



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.

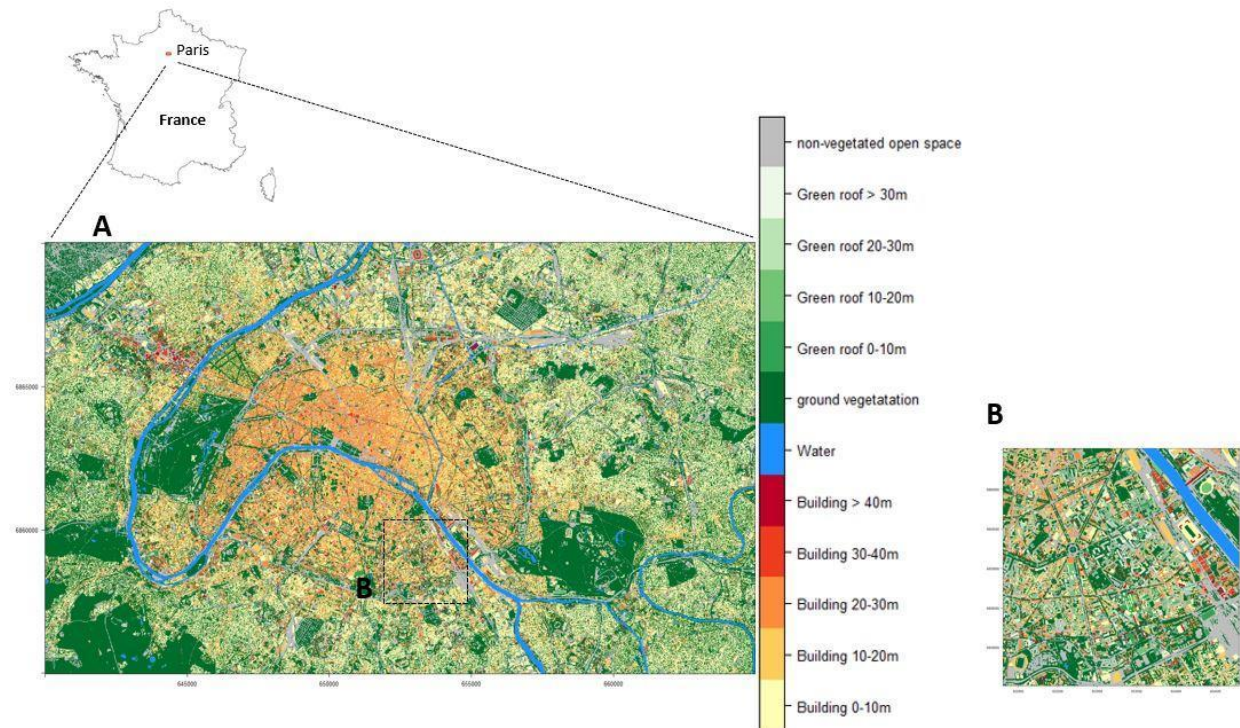
90

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 km²,
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 m² 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 α ($0 < \alpha < 1$) 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 β . As the green roofs' surface
205 area is much smaller than green spaces' area (Table 2), the parameter β 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 m².
219 95% of those patches were ground green spaces and represented 99% of the vegetated area (in m²)
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 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

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.

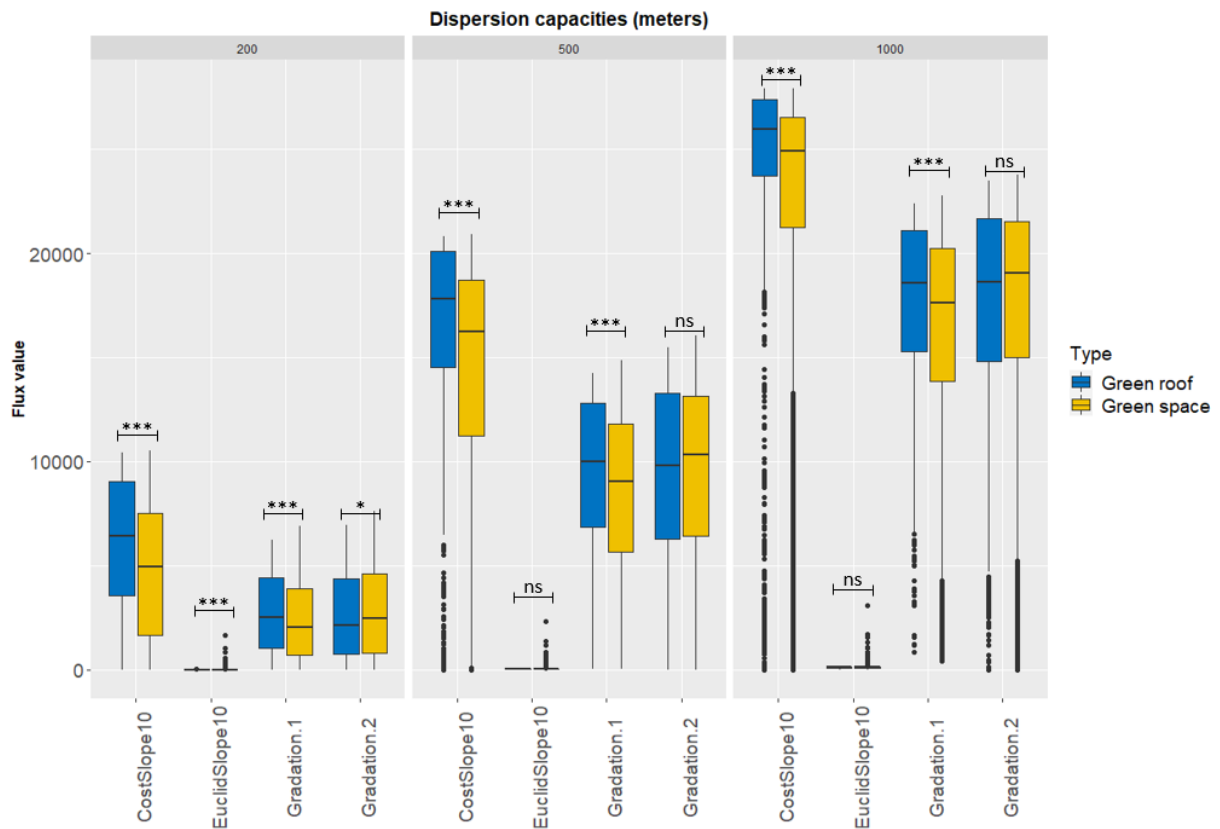
Distances	with/without green roof – gradation 1		with/without green roof – gradation 2	
	a_i =area (A)	a_i =1 (B)	a_i =area (A)	a_i =1 (B)
200	1.87%	12.95%	1.49%	10.44%
500	2.46%	11.75%	2.07%	10.15%
1000	2.69%	10.92%	2.35%	9.86%

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.

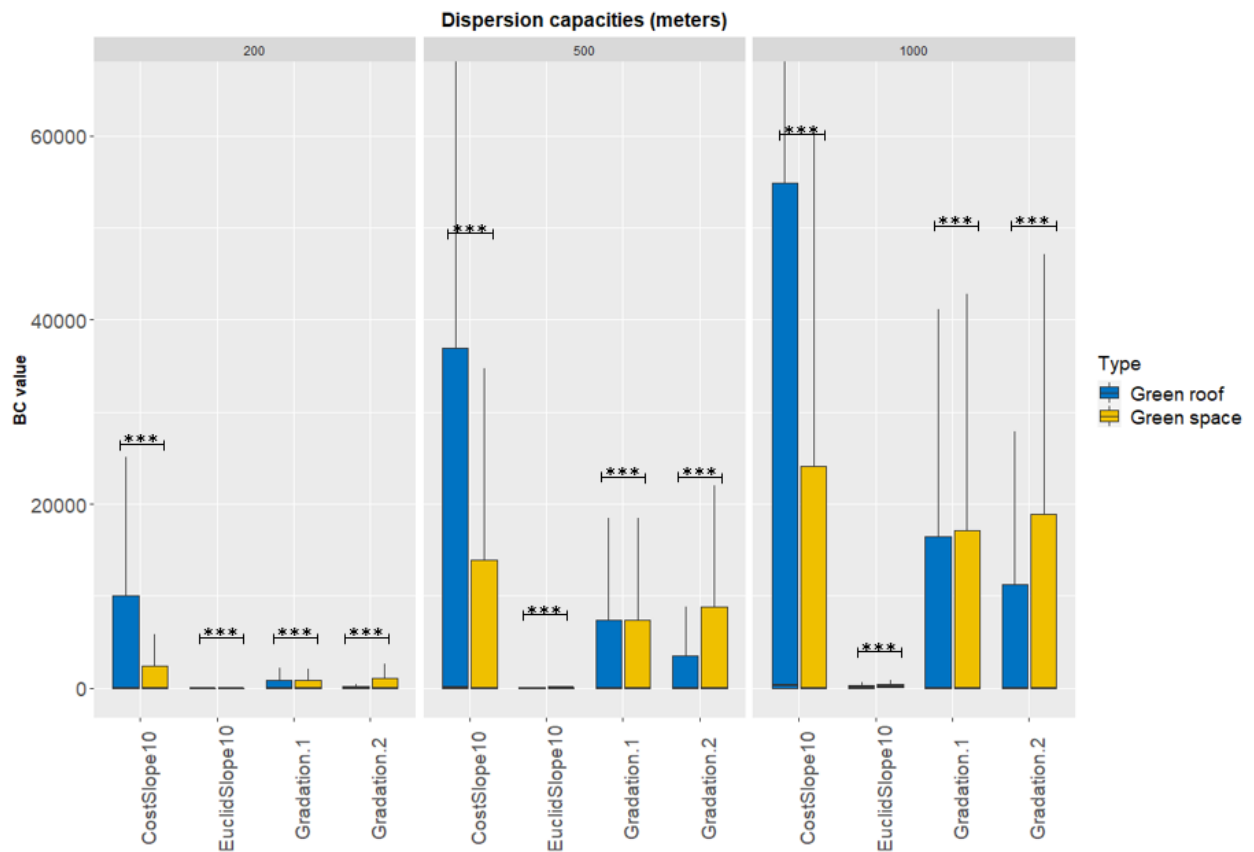
245 **Figure 2:** Comparison of the Flux (F) values between green roofs and ground green spaces for the four
 246 resistance gradations and the three dispersion capacities. Stars represent significance levels from
 247 Wilcoxon's test.



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

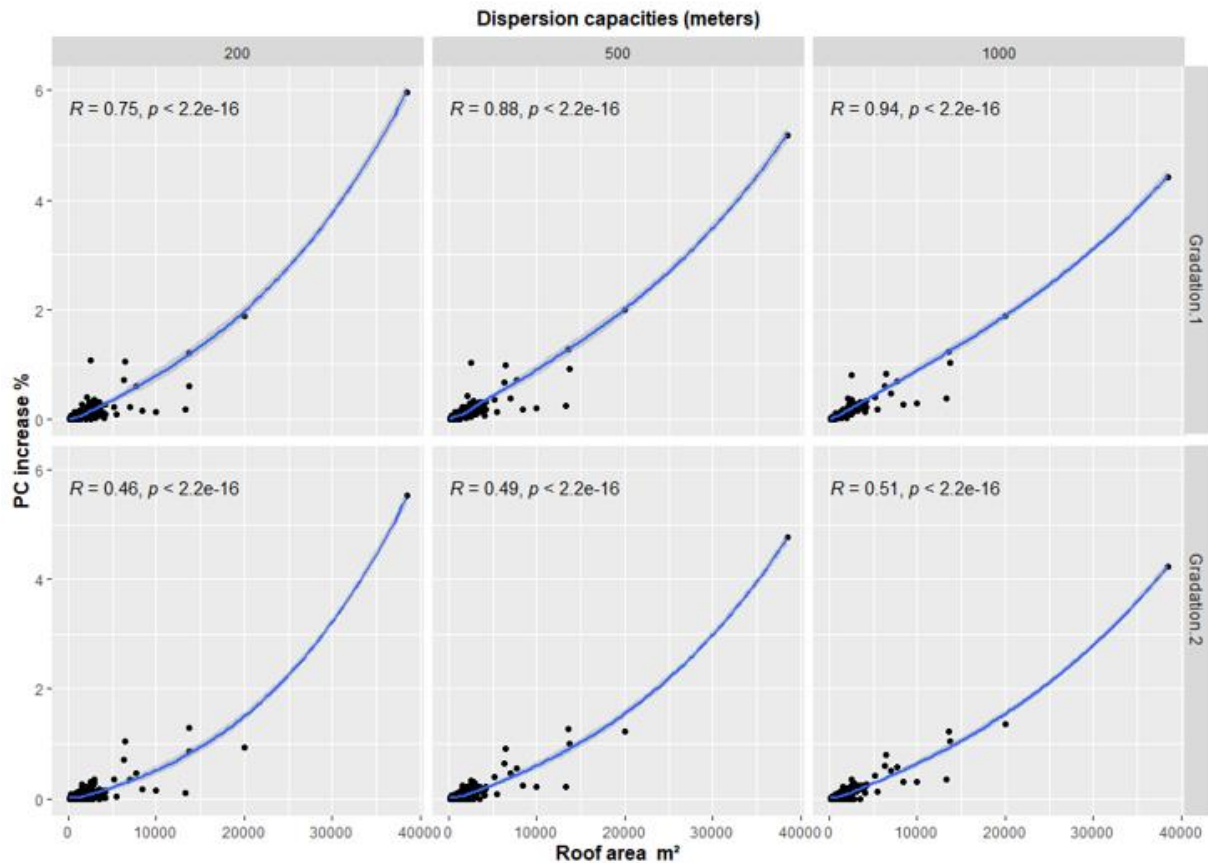
262 Many green roofs had a zero BC value, meaning they were not central in the network (Appendix A):
 263 31% with EuclidSlope10, 47% with CostSlope10, 56% with gradation 1 and 65% with gradation 2. As
 264 comparison, the proportion of zero values was lower for ground green spaces except with CostSlope10
 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 m²), 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 (m²), the dispersion capacities of species, the resistance gradations 1 or 2. R and P-value
 287 corresponding to the Spearman correlation test.

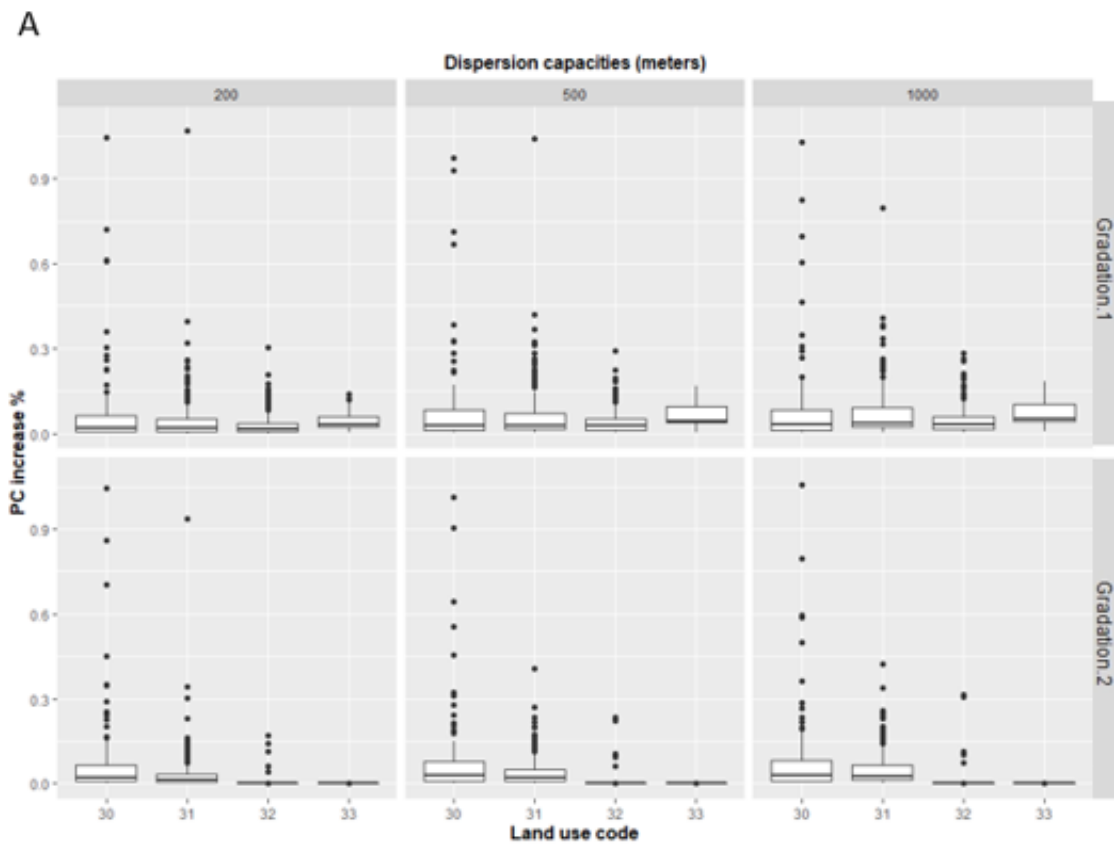


288

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 ($a_i=1$).

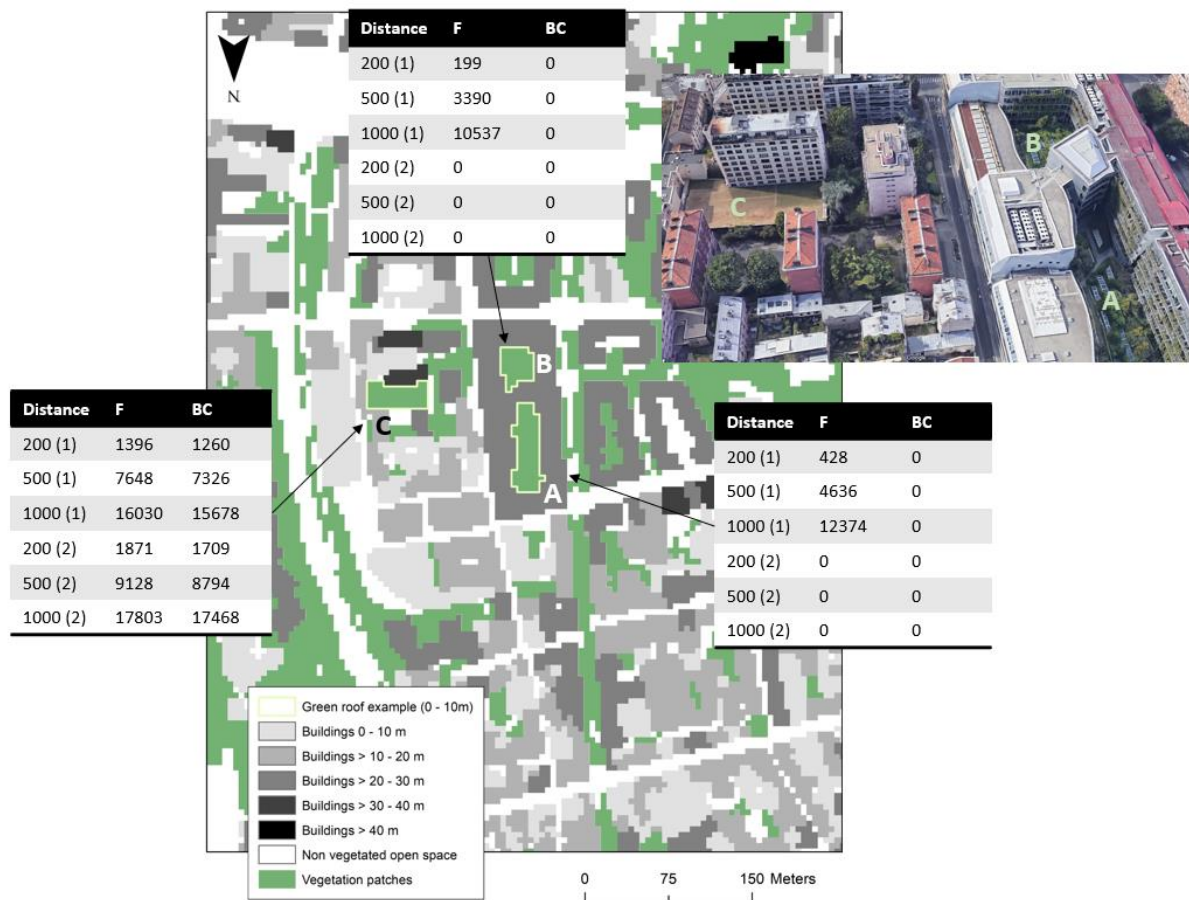
315 At the patch scale, green roofs often have higher Flux values (Figure 2) and lower BC values (Figure 3)
316 than ground green spaces. This suggests that they have more of a role in terms of dispersal flows than
317 as connectors between habitats, especially for relatively and highly mobile species. 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 100m², a
371 resolution of 25m² 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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588

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
594 (Figure 1A).

595 **Table 3:** Global connectivity rate of change measured by the probability of connectivity (PC) including
596 or excluding green roofs for the two resistance gradations and the three groups of species according
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
603 resistance gradations and the three types of dispersion capacity. Stars represents significance levels
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
607 levels from Wilcoxon's test.

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.

611 **Figure 5:** potential gain in probability of connectivity (PC) from greening new roofs according to their
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,
615 i.e. Land use code 30 and 31).

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)
618 are connectivity index explained in the method section.

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

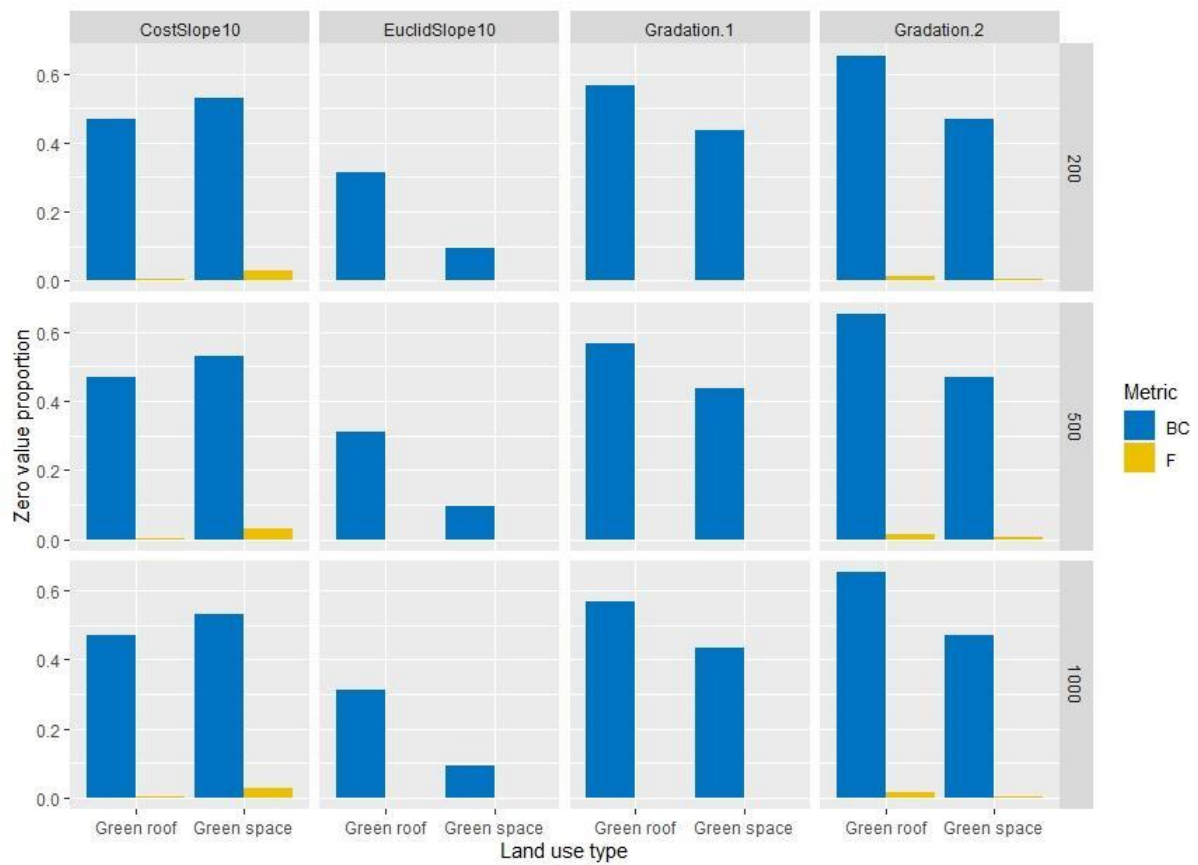
622 **Appendix B:** Zero values proportion for the BC (betweenness centrality) and F (flux) index, as a function
623 of green roof height according to surface type, connectivity index, links calculation methods and
624 dispersion capacities

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

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

629 **Appendices:**

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

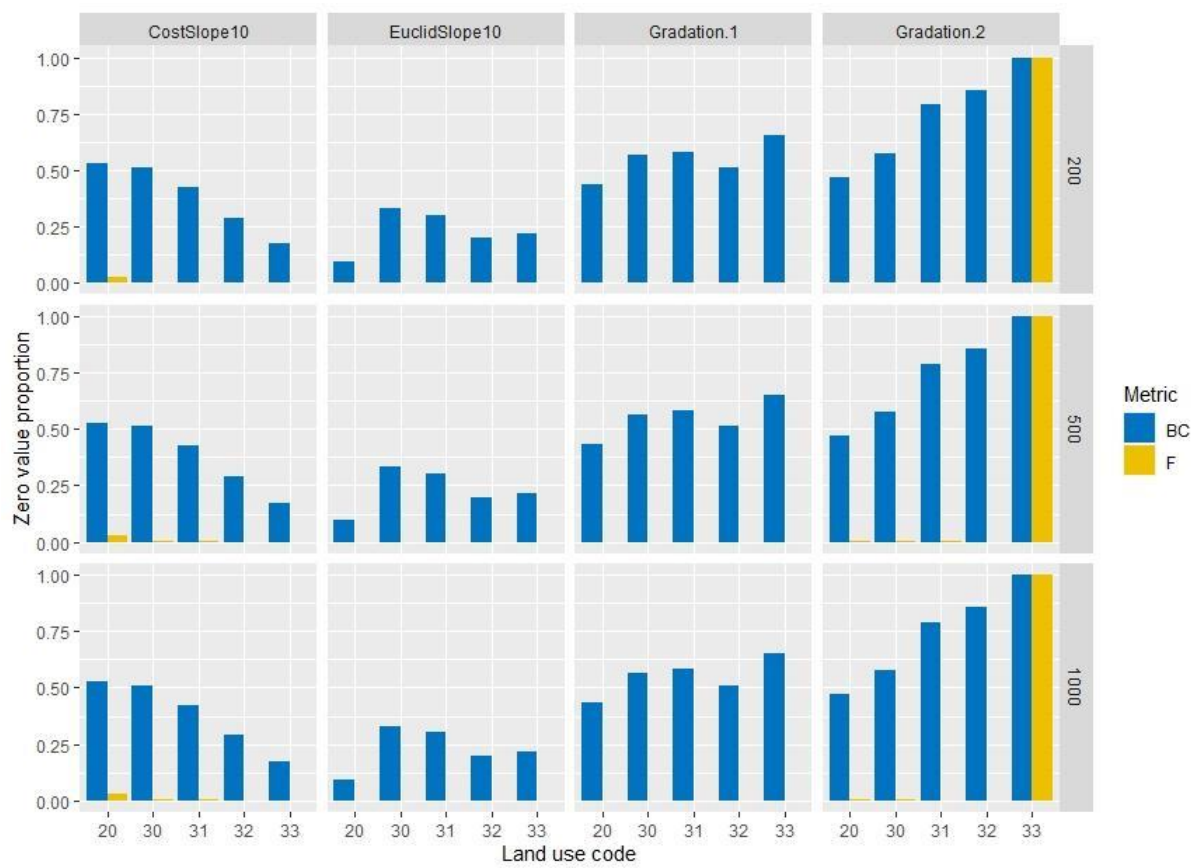


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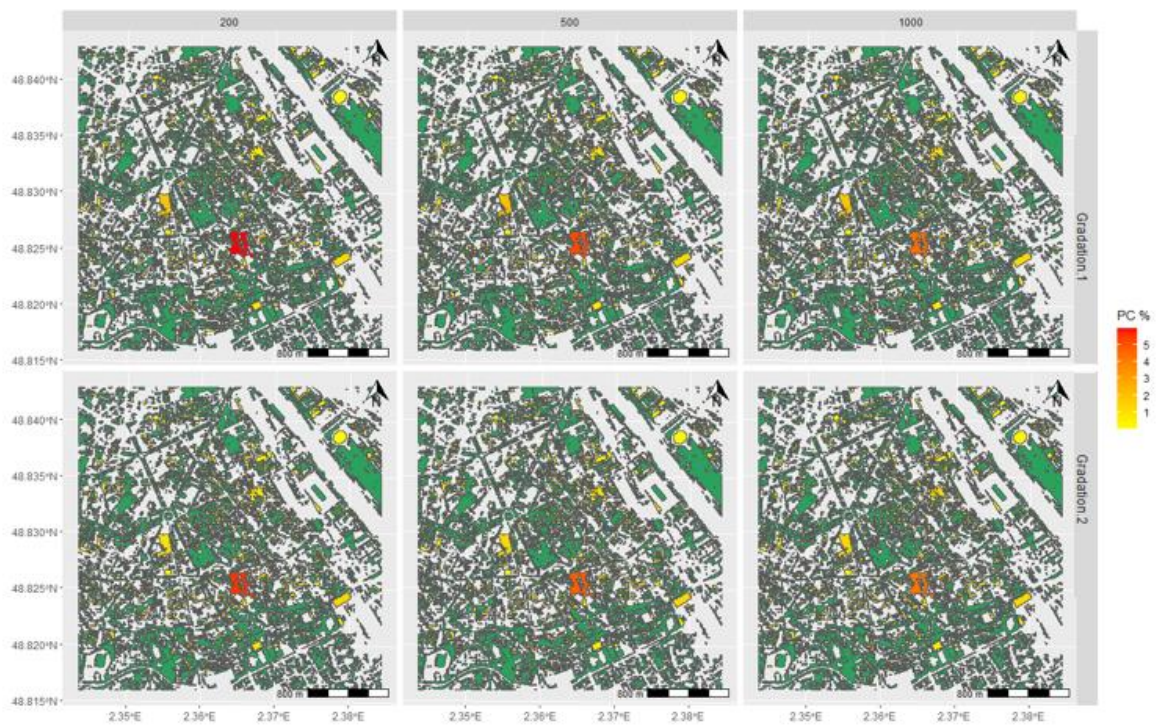
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635 of green roof height according to surface type, connectivity index, links calculation methods and
636 dispersion capacities

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

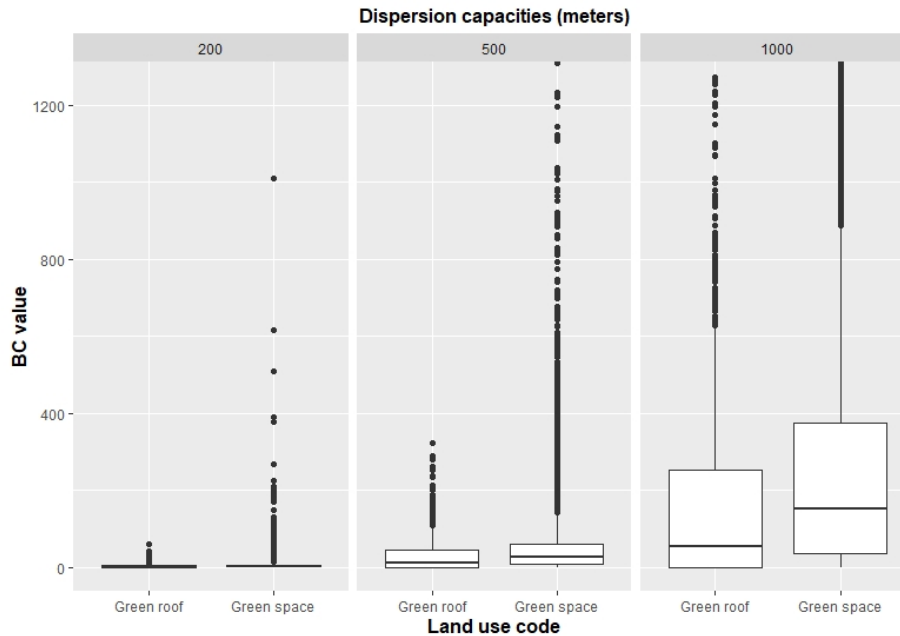


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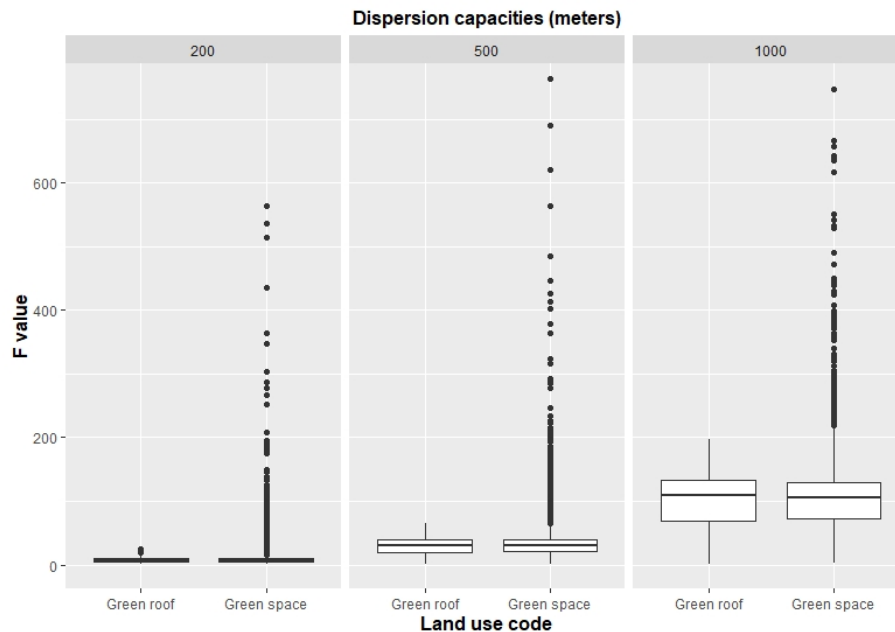
642 **Appendix D:** Zoom on EuclidSlope10 links calculation method. Comparison of the F (flux) (A) index and
643 the BC (betweenness centrality) (B) index between green roofs and ground green spaces for the three
644 types of dispersion capacity.

A



645

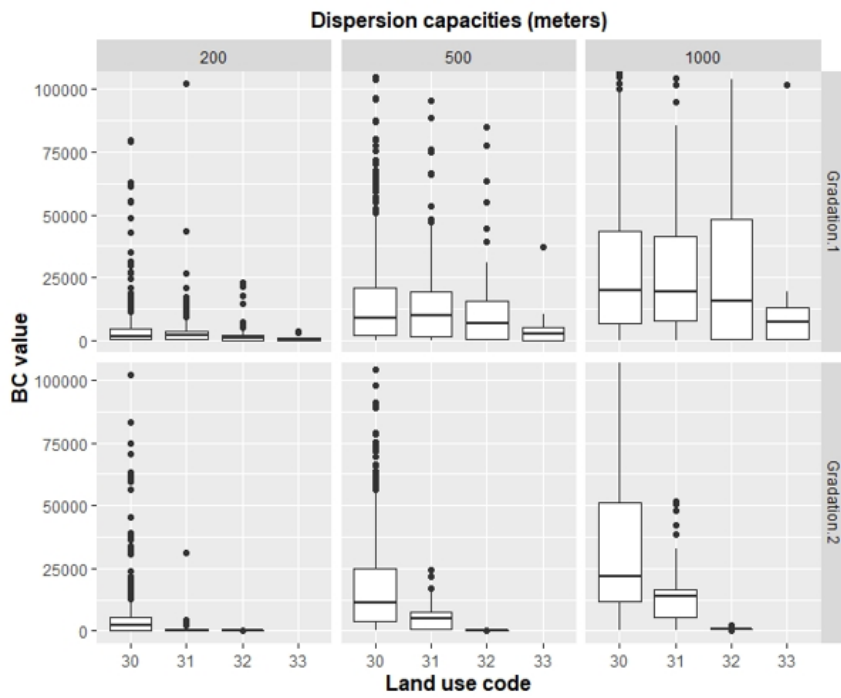
B



646

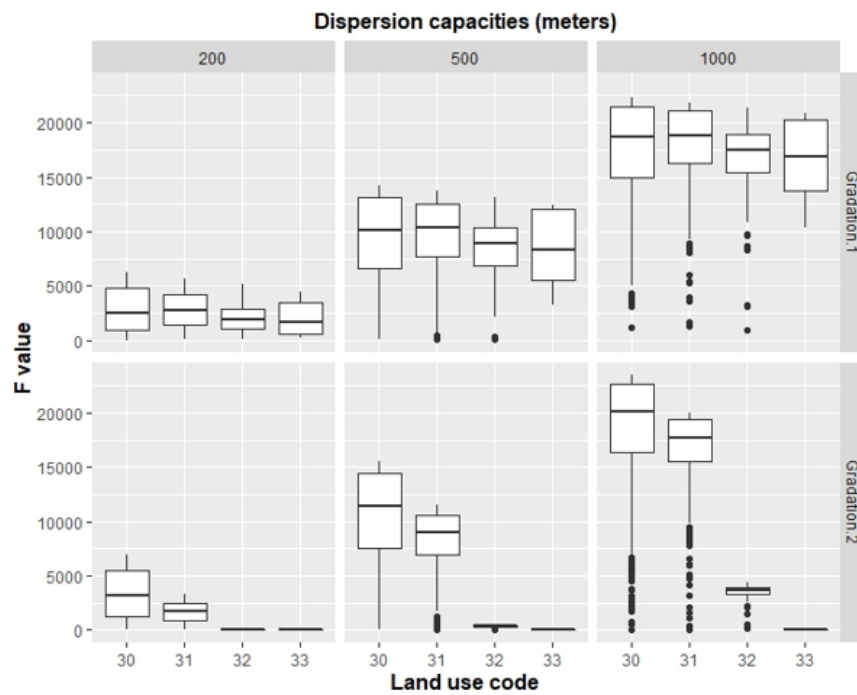
647 **Appendix E:** Comparison of the BC (betweenness centrality) values (A) and the F (flux) values according
648 to the height of the green roof. Only 90% of the positive values were represented (quantile from 5 to
649 95). **30:** green roofs > 0-10 m; **31:** green roofs > 10-20 m; **32:** green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

A



650

B



651