Fractal analysis of green roof spatial implementation in European cities

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Summary

To face the consequences of climate change and unsustainable urbanization, green roofs are currently widely implemented in urban environments. Despite their benefits to restore ecosystem services are quite well established at the roof scale, green roofs need to be widely and appropriately distributed to perform efficiently at larger scales. However for now, this scale-factor is not considered to guide and conduct green roof implementation policies.

Here we show that a multi-scale analysis based on fractal theory is helpful in providing information for green roof implementation and in assessing the relevance of these policies.

We found the fractal dimensions computed for green roofs are sparse, ranging from 0.49 to 1.35 for the nine studied cities, and illustrate some different degrees of progress in urban greening. Our results demonstrate some significant inconsistencies between political ambition and their *in situ* realization, and the necessity to better take into account the spatial distribution of green roof implementations in order to optimize their performances.

Introduction

Green roofs (GR) are currently widely implemented in urban environments, as they represent one of the possible assets to contribute to the re-naturation of

cities. Considered as Nature-Based Solutions (NBS) or Blue Green solution (BGS), green roofs are recognized as multifunctional tools able to provide several ecosystem performances (Francis and Jensen, 2017; Oberndorfer et al., 2007) to face climate change and unsustainable urbanization consequences. They appear to be particularly relevant in thermal regulation (Santamouris, 2014; Suter et al., 2017), biodiversity support (Cook-Patton and Bauerle, 2012; Madre et al., 2014), air quality improvement (Baik et al., 2012; Speak et al., 2012) and above all storm water management (Stovin et al., 2012; Versini et al., 2016).

The implementation of only one green roof usually performs well at the building scale but becomes negligible at a larger scale. To be really efficient at large scale (neighborhood, district, city), a wide diffusion of this technique is required. Nevertheless, they have to be appropriately spatially distributed to perform efficiently in a complex urban environment. To optimize this layout, traditional assessment tools, like densities, are not appropriate, as they do not take into account the relationship between different areas, i.e. across scales. Indeed, urban areas are considered as complex systems constituted of different elements spatially distributed in a rather non-uniform way, and clustered at different scales. Buildings from different sizes can be regrouped in blocks, neighborhoods, and urban areas characterized by irregular shapes and constituting *in fine* an agglomeration. To describe and assess the layout of buildings through these scales, traditional assessment tools are not suitable as they consider the mean occupation of space rather than their morphological arrangement. Fractal analysis, based on the concept of scale invariance, assumes similar patterns are visible at all scales (Mandelbrot, 1983). It characterizes how much a studied field - too tortuous to be characterized with the help of the classical Euclidian

geometry- fills its embedding space not only at a single scale (usually at the maximum resolution), but across the scales. Fractal analysis had been used in geophysics (Lovejoy et al., 1986) although these non geometrical fields rather require a multifractal analysis of their non binary intensity (Lovejoy et al., 1987a; Schertzer and Lovejoy, 1987). Characterized by some more geometrical distributions exhibiting strong heterogeneity over a wide range of scales, urban areas appear to be particularly adapted to fractal analysis (urban fabric, transport network, sewer system or settlement for instance (Benguigui, 1995; Dupuy, 2017; Feng and Chen, 2010; Gires et al., 2017)). Here, for first time, fractals are used to evaluate the efficiency of greening policies in European city centres by analysing the geometrical fields composed by green roofs.

Methodology

In order to form a representative and homogeneous dataset of green roofs dissemination in Europe, the following strategy was carried out. First the European Federation of Green Roofs and Walls (EFB, https://efb-greenroof.eu/) was contacted. Based on a discussion with its president and on the European database presented in Figure 1, several countries were prioritized, including Germany, France, Switzerland, UK, Holland, Scandinavia, Austria, and Belgium. The national green roof federations and numerous cities were then questioned about the availability of such geographical information, meaning the exact location where green roofs are implemented. Many of them have answered and we finally put together a sample of 9 cities (see Figure 1): Paris and Lyon (France), Amsterdam (Netherlands), Central Activities Zone of London (UK), Berlin and Frankfort (Germany), Geneva (Switzerland), Copenhagen (Denmark), and Oslo

(Norway). Most of these cities have launched some incentive policies to promote the implementation of green roofs. Collected data are shortly presented in the following. They were produced by external organisms and usually obtained relying on a remote sensing approach combining infrared and visible light orthophotos (aerial images) with building numerical models. Orthophotos treatments allow a spectral differentiation of types and materials of roof covers, and the identification of vegetation is facilitated due to its strong reflecting properties in the near infrared.

Taking benefits from the EFB association network and the EU initiative related to green infrastructures (European Commission, 2016), this study was conducted and focused on European countries. Nevertheless, additional green roof policies exist around the world (but not necessarily the corresponding data), especially in US, China, Canada, Singapore or Australia. Similar study could be done under the condition that appropriate geographical information is available.

Amsterdam (Netherlands)

This green roof database belongs to the Municipality of Amsterdam (Space and Sustainability Unit) and can be downloaded from the Maps Data webpage (https://maps.amsterdam.nl/open_geodata/). They are available for the entire city (218.7 km^2). The greater part of the georeferenced roofs have benefited from a subsidy provided by the Amsterdam municipality. Additional green roofs have been added by citizens in a collaborative way. This collection is being processed since 2010 until now. In order to assess its reliability, a visual verification has been done and few missing green roofs have been added. Finally, 479 green roofs have been listed.

Berlin (Germany)

The "Environmental Atlas Berlin / Green Roof" data set has been produced by the Senate Department for Urban Development and Housing of Berlin (http://fbinter.stadt-berlin.de/fb). A specific procedure was developed to produce this data that is explained in details (Coenradie and Haag, 2016). It combines an automated preliminary mapping, including determination of reference areas, and then the review and improvement of these results by means of interpreting aerial images. The automated preliminary mapping is based the spectral analysis of digital colour-infrared orthophotos (from April 2016) combined with building and roof outline geometries on the whole Berlin city (891.8 km^2). As only vegetation was selected -making some complex patches on buildings- this data has been crossed with roof footprint to be comparable to the other data. Finally, 13,865 greened buildings have been selected.

Copenhagen (Denmark)

The dataset containing the information about existing green roofs in Copenhagen (88.2 km^2) was provided by the Technical and Environmental Management service of the Municipality (not in open access). It consists of polygons manually drawn by using aerial photographs (2013), and a national building register in order to focus the selection on existing buildings. This dataset has not been updated from its creation and lists 321 vegetated roofs.

Frankfort (Germany)

The inventory of existing green roofs in Frankfort (248.3 km^2) was provided by the Environmental Department of the City. Data was produced in collaboration

with the German Aerospace Center (DLR) in the framework of a project untitled "Remote Sensing of Vegetable Landscapes on Roofs for the Development of Urban Climate, Urban Drainage and Species Conservation Potential for urban areas ". For this purpose, 4-channel (color and infrared) aerial images (from 2015) were used and crossed with building data set of the City Surveying Office for the entire city area. Based on the analysis of existing green roofs, a series of parameters related to vegetation cover, roof shape and pitch have been defined and combined to select potential green roofs. After a manually checking, this methodology has allowed the identification of 15,798 green roofs.

Geneva (Switzerland)

Green roofs have been reported on the whole Canton of Geneva (282.3 km^2). This data was produced through a collaboration between the Conservatory and Botanical Gardens of the City of Geneva and the General Direction of Agriculture and Nature, and are available from the Geneva territory web page: http://ge.ch/sitg/sitg_catalog/sitg_donnees. True colour and infrared aerial images (from 2011) were combined with some digital surface and terrain models to compute 4 indicators: roof slope, brightness, presence of vegetation, and roof surface. Threshold values adjusted on these indicators were then used to determine existing green roofs. Finally, 2,393 green roofs have been listed after a visual control.

London (United Kingdom)

Green roofs geometries have only been computed on the Central Activities Zone (CAZ, 33.4 km^2) representing 2% of London's total area. This data was produced

by Hannah Collis from King's College London and is available from the London Datastore webpage (https://data.london.gov.uk/dataset/central-activities-zone-boundary-london-plan-consultation-2009). True colour and infrared aerial images (from 2015) were combined with a digital elevation model to select the raised vegetation. On the London's CAZ, 475 green roofs have been listed.

Lyon (France)

Green roof data was extracted from the "Vegetated layer" regrouping 14 types of vegetated surfaces (meadows, crops, lawns, forests…). This dataset was produced by Métropole du Grand Lyon in 2013, and is available from the Data Grand Lyon web site (https://data.grandlyon.com/). They were computed by using orthophotos (2009), infrared images, and a digital surface model. Produced on the whole metropolitan area, only green roofs implemented on the city of Lyon have been selected. On this dense urban area (47.9 km^2), 336 existing green roof have been listed.

Oslo (Norway)

This data was provided by the Planning and Building Service from the City of Oslo (https://www.slideshare.net/GeodataAS/grnne-tak-i-oslo-irortofoto-bidrar-til-bedre-grnn-by-bk2016). It is based on a spatial analysis carried out by combining orthophotos (from 2013), satellite pictures (from 2014) and building footprint database. Some classification rules were defined to recover green roofs. This method was tested and calibrated by using a sample of existing green roofs and by computing a maximum likelihood. Finally, 614 green roofs have been reported on the county of Oslo (454 km^2).

Paris (France)

This inventory was achieved by APUR (Atelier Parisien d'Urbanisme, https://www.apur.org/fr) for the Municipality of Paris (not yet in open access). It was produced by combining the InterAtlas aerial pictures (2008), a digital elevation model and a specific geographical layer regrouping geometrical (surface, elevation) and historical (year of construction) properties of existing terrace roofs. The selected green roofs units were then updated with the help of the GERCO database containing building permits on the 2008-2011 time period. Finally, 349 vegetated buildings representing a total area of 34 ha (roofs covered with pots were excluded) were listed in the city of Paris (105, 4 km^2). Note that they are mostly located in the surrounding districts of Paris.

These dataset have been completed with buildings information downloaded for every studied city from the Geofabrik's server (https://download.geofabrik.de/). Extracted from the OpenStreetMap project, this data (called undifferentiated roofs in this paper) provides the footprint of all the listed buildings (location and geometry in shape file). This data were vizualized and analysed with the opensource Geographical Information System tool QuantumGIS (https://qgis.org/fr/site/).

Traditional numerical procedures of Box-counting algorithm (Hentschel and Procaccia, 1983; Lovejoy et al., 1987b) were used to analyse scaling behaviours and compute fractal dimension D_f at different scales for both green roofs and undifferentiated roofs fields. Let us consider a geometrical object (a green roof) of

outer scale l_0 observed at various scale l (i.e. pixels of size l in our 2D case). The spatial resolution is defined as the ratio between the outer scale and the observation scale: $\lambda = \frac{l_0}{l}$. For a fractal field, the fractal dimension D_f is the exponent characterizing the power law relation between the number of non-overlapping squares $N(\lambda)$ of size l needed to completely cover the field at resolution λ and this resolution:

$$N(\lambda) \propto \lambda^{D} \quad \text{(Eq. 1)}$$

In practice, the process is initiated at the highest resolution available (it has been fixed to 1 m in this study), and λ is decreased by multiplying pixel size by 2 at each step, up to a maximum pixel size and lower resolution that covers the whole studied area. At each step, four adjacent pixels are merged. Once non-overlapping green roof pixels of size l are counted for each spatial resolution, Eq. 1 is plotted on a log-log scale. For a fractal set, the points are aligned and D_f corresponds to the straight line's slope. In some cases, distinct scaling regimes can be identified meaning that different fractal dimensions are needed, each representative of the behaviour over a range of scales.

To implement this methodology and to compare similar areas, square zones (whose size is characterized by a power of two) were selected for each studied city. A particular attention was paid to select square areas matching with urban areas completely concerned by green roof inventories. For this reason, the size of the selected square varies from 4096 m to 16,384 m depending on the city. These selected areas are represented in Figure 1 and have been put in perspective with average yearly green roof implementation data provided by the European Federation of green roofs and walls (https://efb-greenroof.eu).

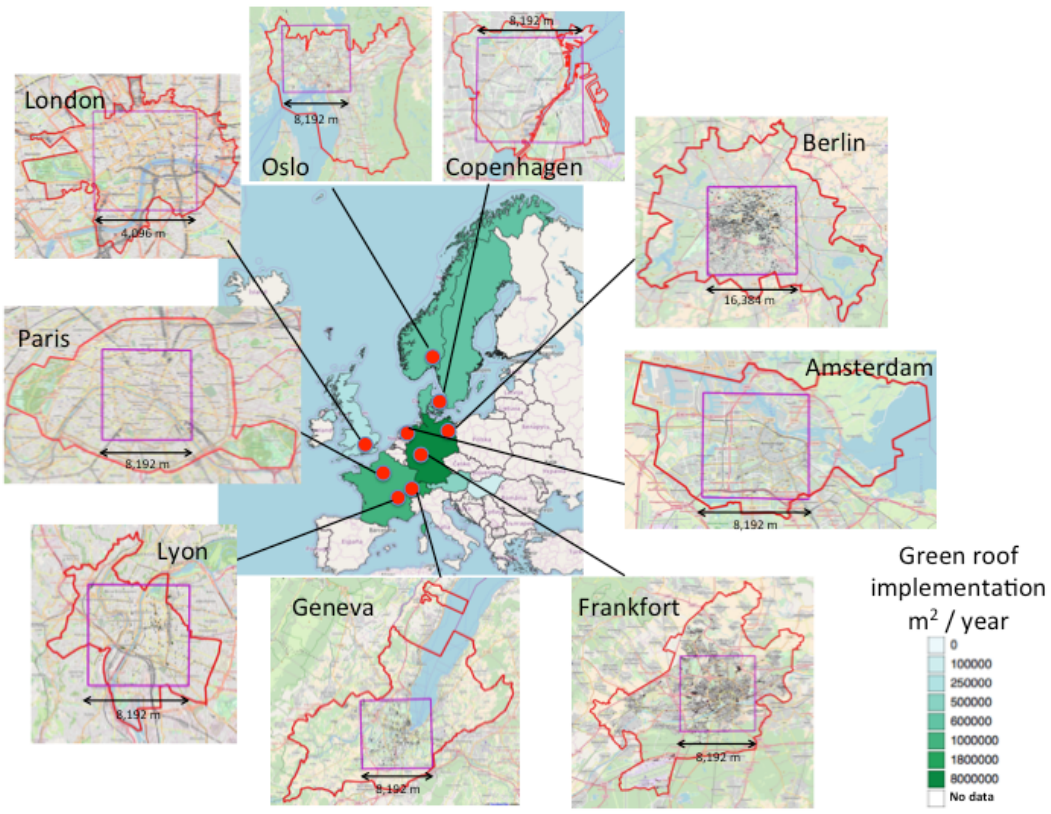


Figure 1. Annual green roof implementation in European countries estimated from the European Federation of Green Roofs and Walls (EFB) database. For the studied European cities, red polygons represent cities contours where green roofs inventories were available and purple squares the areas over which fractal dimensions were computed.

In order to provide additional information about the urban configurations, distributions of both undifferentiated and green roofs' areas have been drawn. They are represented in Figure 2 and depict significant differences in terms of buildings' size. Indeed, Amsterdam, Frankfort and Geneva are characterized by rather small roof tops (at least 80% are lower than 250 m^2), while Lyon and Paris have rather large roofs (more than 60% are higher than 250 m^2). Distributions computed for undifferentiated and green roofs have usually similar shapes.

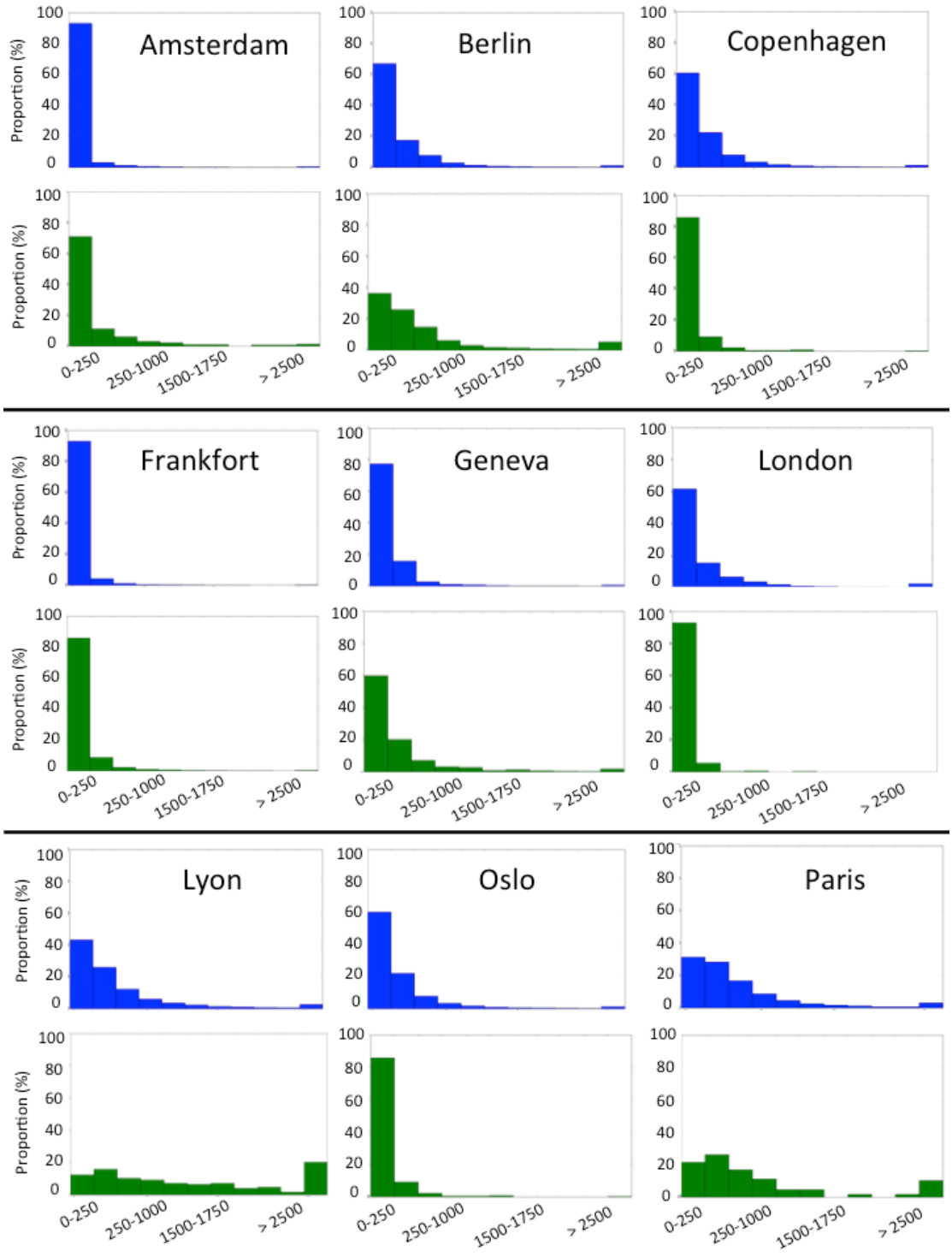


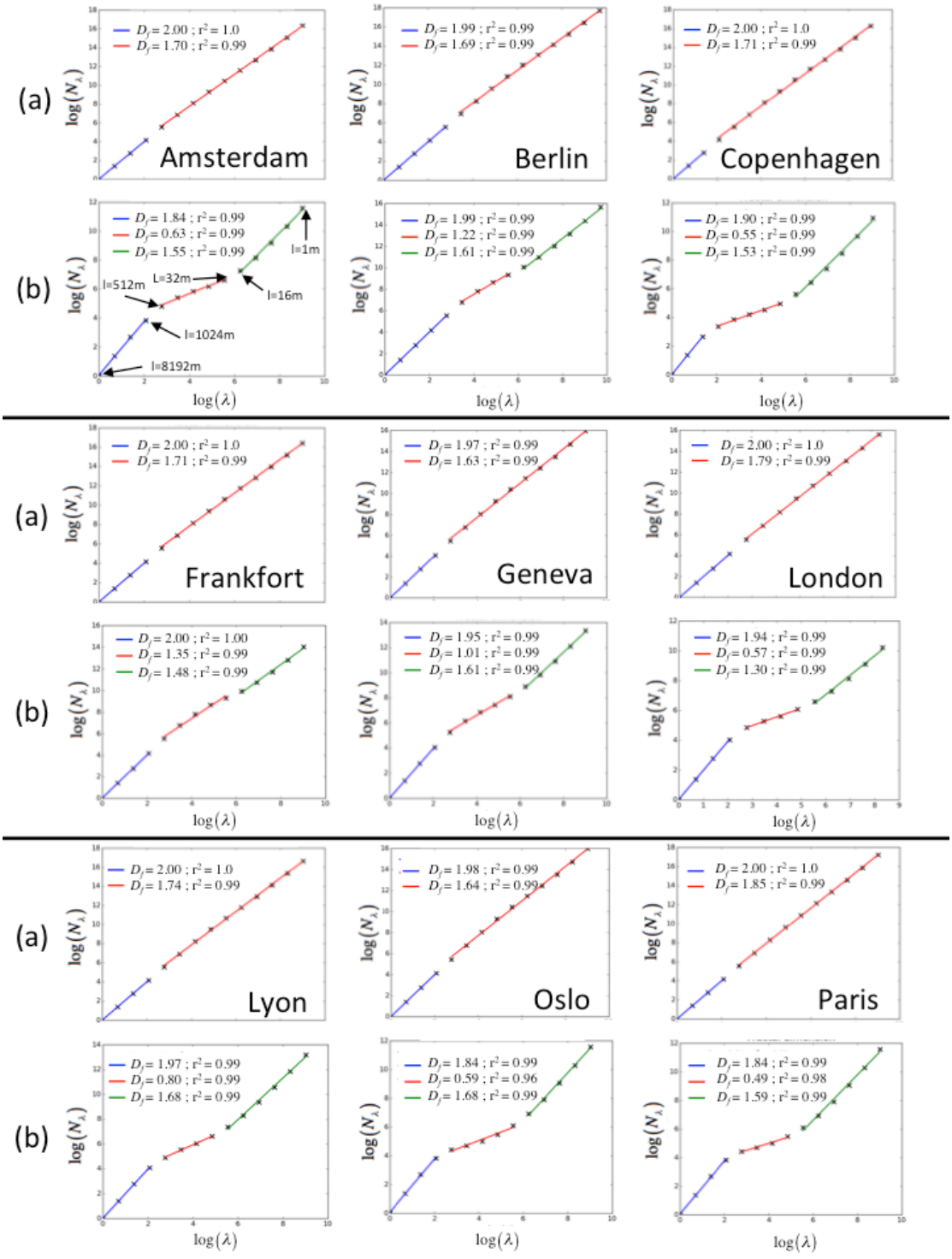
Figure 2. Distribution of undifferentiated (blue histogram) and green (green histogram) roofs' areas

Presentation of the results

Eq(1) is plotted in log-log in Figure 3 for both undifferentiated and green roofs, and for the various cities. The corresponding computed fractal dimensions are synthetized in Table 1.

	Paris	Lyon	Amsterdam	London	Berlin	Frankfort	Geneva	Copenhagen	Oslo
Size (m)	8,192	8,192	8,192	4,096	16,384	8,192	8,192	8,192	8,192
Roofs #	47,093	31,532	105,327	14,119	160,970	131,852	40,226	29,020	23,208
GR #	106	290	335	301	8,593	8,751	1,629	232	344
GR_A (ha)	14.1	52.6	10.86	2.9	661.6	125.9	65.3	5.6	5.1
GR_D (%)	0.21	0.78	0.16	0.17	2.46	1.87	0.93	0.08	0.74
D_f_UR	1.85	1.74	1.70	1.79	1.69	1.71	1.63	1.71	1.64
D_f_GR	0.49	0.80	0.63	0.57	1.22	1.35	1.01	0.55	0.62

Table 1. For each studied city: Size of the square zone where the computation was done, Roofs # and GR # represent the number of roofs and green roofs in the square studied area, GR_A total green roof area computed in the studied squares (ha), GR_D green roof density (%), fractal dimensions D_f_UR computed for undifferentiated roofs (1st regime) and D_f_GR computed for green roofs (2nd regime)



Figures 3. Fractal dimension computed from Eq (1) in log-log plot for undifferentiated roofs (a) and green roofs (b). r^2 criterion are mentioned to assess the quality of the regression and the underlying scaling behaviour.

Similar results were obtained for all studied cities and can be summarized as follow: green roofs fields are characterized by three distinct scaling regimes, whereas only two scaling regime would be sufficient to fully characterize the behaviour of undifferentiated roofs distributions (one for scales ranging from 1 m to 512 m and another from 1024 m to the entire studied window). Scaling regimes are robust with solid lines and r^2 is always comprised between 0.95 and 1.0.

This first regime (for small scales, in red on Fig. 3) defined for undifferentiated roofs is characterized by a fractal dimension close to 1.7 for all cities. More precisely, it ranges from 1.63 for Geneva to 1.85 for Paris. The variations around this value actually reflect disparities in terms of level of urbanization for the various studied areas, which is in agreement with previous results obtained in European metropolitan areas (Frankhauser, 2004; Gires et al. 2017). At these scales, roof surfaces are densely distributed (that is why D_f is close to 2, the dimension of the studied area), but they are embedded in an environment comprising additional types of landuse (street, parking, green areas…). The fractal dimension computed for the second regime (large scale, in blue on Fig. 3) is almost equal to 2, which is the dimension of the studied field. It means that from this observation scale of 1024 m, the space is fully filled by roofs due to the high density of buildings into the city and the absence of large (natural) bare spaces.

The large scale regime for green roofs with high fractal dimension (from 1.84 to 2.0) is quite similar to the one computed for undifferentiated roofs (on blue in Figure 3). It characterizes the space filled by green roofs at very large scales. The lowest values are obtained for Amsterdam, Oslo and Paris, where a significant

heterogeneity in the green roofs field can be noticed. In addition, the small scale regime should be separated into two sub regimes.

The first one corresponds to the inner scales (in green on Fig. 3) of green roofs. The upper scale limit is not clearly defined and is between 16 m and 32 m according to the city. This very small scale regime is characterized by a fractal dimension tending to 2, and simply reflects the 2D nature of green roofs. It basically means that green roofs tend to be installed on buildings with typical size greater than ~ 16 m (~ 256 m^2). As it can be seen in Figure 2, almost all green roofs are characterized by an area lower than 500 m^2, except for Paris and Lyon, and to a lesser extent Berlin. This upper limit of few tens of meters depends on the area. It corresponds to the minimum size of typical green roof. Its assessment is actually not robust since it corresponds more to a point in the transition between the middle scale regime (next paragraph) and the very small scale regime where D tends to 2.

The second one corresponds to the intermediary regime (between 32 or 64 m and 256 m or 512 m). It characterizes not only single roofs but their distribution in space which is what we are interested (in red on Fig. 3). Fractal dimension characterizing this regime is highly variable from one city to another, ranging from 0.49 for Paris to 1.35 for Frankfort. These fluctuations illustrate a real difference between roof vegetalization in European urban centres. This suggests that for now and given the current stage of green roofs deployment there is no intrinsic relation between green and undifferentiated roofs, and that the distribution of green roofs is hence strongly influenced not by universal underlying city features but by political will and the architectural history. The scale boundaries of this regime seems also to be an indicator of green roof distribution. It seems to characterize

their size (area). The upper boundary is usually equal to 32m except for Berlin, Lyon and Paris for which it is equal to 64 m (corresponding to a pixel area of 4096 m^2). Regarding Figure 2, it appears that these 3 cities are characterized by rather large sizes of green roofs.

Such curves highlight the benefits of using a scale invariant notion of fractal dimension rather than a single % defined at the maximum resolution. Indeed such indicator basically corresponds only to the information given by the last point on the right of curves in Figure 3 (l=1m), while the fractal dimension contains information across scales. For the green roofs cases, it is even more striking because of the presence of three scaling regimes as previously discussed.

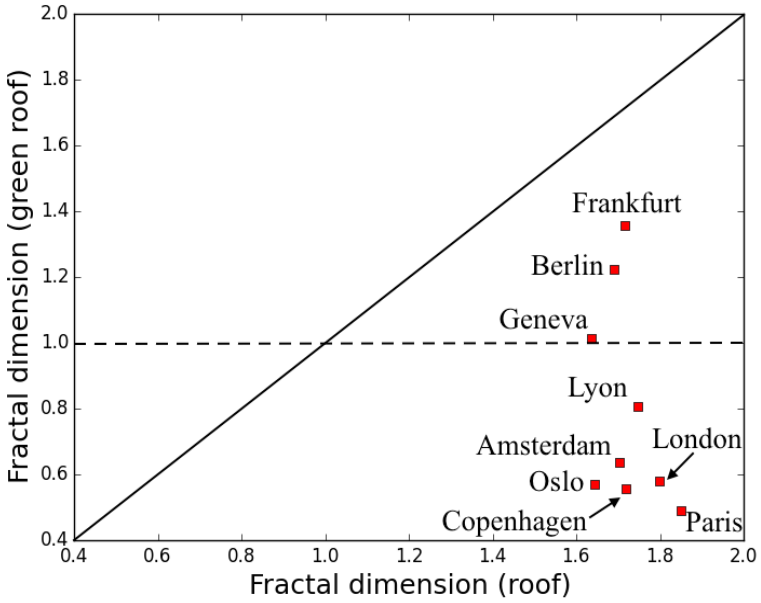


Figure 4. Comparison between fractal dimensions computed for undifferentiated and green roofs

Although cities with the highest green roofs areas and densities seem to have the highest fractal dimension, the lack of direct correlation between both metrics provides some relevant information about the spatial layout of green roof in some

heterogeneous urban environments. It is for instance the case for the fractal dimension of the impervious areas and the undifferentiated roofs (Gires et al., 2017). This suggests that in the case of green roofs vs undifferentiated roofs, there is no intrinsic relation between the two (see Figure 4), and that the distribution of green roofs is hence strongly influenced not by universal underlying city features but by political will and the architectural history. This might change once a maximum of green roofs are commonly implemented, but this is not yet the case. In Order to find some causes of these differences, the green roof policies implemented in the studied cities have been synthetized in Table 2. Three different categories have been defined: (i) Political will: official documents promoting green roof without proposing any support, (ii) building regulation: rules imposing the presence of green areas, and (iii) incentive program: monetary subsidies reducing the cost of investment.

Amsterdam	- Incentive program covering 50% of the installation costs, with a maximum value of up to 50 €/m^2 (since 2009)
Berlin	- Incentive program reducing the precipitation water fee for green roofs (only 50% of the area is considered) (since 2000) - Building regulation imposing a green area in new buildings called Biotope Area Factor (since 2014) - Incentive program covering up to 100% of the installation costs, with a maximum value of up to 60 EUR/m^2 and 60,000 EUR/building (since 2018)
Copenhagen	Building regulation imposing green roofs for all new buildings with roof slopes of less than 30 degrees (since 2010)
Frankfort	Incentive program covering 50% of the installation costs, with a maximum of 50 k€ (since 2018)
Geneva	- Political will: Nature in the City Plan (2012) - Incentive program that funds up to 50% of the total cost of an infrastructure promoting biodiversity, and their maintenance during 3 years (since 2013)
London	- Political will: Environment Strategy document (2018) - Building regulation with the application of a Green space factor to secure a certain amount of green cover in every development (since 2019)
Lyon	No particular policy

Oslo	Political will with the 2019 European Green Capital award and the current developing of a green roof strategy which will ensure smart and geographically differentiated use of green roofs as a tool for solving urban environmental challenges
Paris	- Political will with the objective to vegetate 100 ha of walls and roofs before 2020 (in 2014) - Building regulation with the authorization of building overstepping in the case of the greening of roof terraces, then considered as a device contributing to energy savings (since 2009)

Table 2. Green roofs policies implemented in the studied cities. Political will, building regulation and incentive programs have been differentiated.

Let us compare Berlin and Frankfort, two cities with a long tradition in greening roof and facade surfaces, for instance. Berlin has the highest vegetated roof surface (6.6 km^2 representing 2.5% of the studied area), and is characterized by a D_f equal to 1.22. Note that about 2,000 green roofs were already implemented at the beginning of the 19th century (Ahrendt, 2007). Moreover several programs have promoted their implementation during the last decades: (i) a "courtyard greening program" reimbursed 50% of green roof construction costs from 1983 until 1997, (ii) since 2000 only 50 % of greened roof area is considered in calculating the precipitation water fee, (iii) since 2014 a building regulation imposes a minimal green area in new buildings (called Biotope Area Factor), (iv) since 2018 the program “1,000 green roofs” can reimburse up to 100% of the installation costs, with a maximum value of 60 €/m^2 and 60,000 €/building. Frankfort, where less green roofs are implemented in (1.2 km^2 representing 1.9% of the studied area), is however characterized by the highest D_f (1.35). This difference illustrates two different spatial coverages in these cities. The green roofs distribution looks more homogeneous in Frankfort, which was almost completely destroyed during the Second World War, and where many flat-roof buildings were built during the 50s, facilitating now the implementation of green roofs. It is more heterogeneous in

Berlin with a higher concentration of vegetated roofs on the North side of the studied area. Conversely to Berlin, there was no incentive program until recently in Frankfort. This program proposes to fund 50% of the eligible costs for the implementation of a new green roof (with a maximum of 50 k€). Started last year (2018), it cannot be responsible for existing green roofs.

Regarding the cities characterized by low values of D_f, similar analysis can be conducted. Paris, which has higher vegetalized roof surface and density values than Amsterdam, London and Copenhangen, has however the lowest D_f value. This is all the more surprising given that Paris has a very densely and homogeneously built environment. Among the studied cities, it obtains the highest D_f value for undifferentiated (1.85), living few empty spaces between buildings. This poor value showing a very heterogeneous green roofs distribution results from two main reasons: (i) some architectural issue making difficult the roof vegetalization in the inner city due to the presence of historical Hausmanian buildings, (ii) the absence of a global vision framing the implementation of the ambitious plan launched by the municipality of Paris to vegetate 100 ha of walls and roofs before 2020. In comparison, some other initiatives seem to have better results. Since 2009, Amsterdam has launched a green roof incentive program to grant direct subsidies for building owners to install a green roof. The program offers to cover 50% of the installation costs, with a maximum value of up to 50 €/m^2. On its part, Copenhagen is the first Scandinavian city to adopt a policy promoting green roofs. Since 2010, the implementation of green roofs is required on all new buildings with roof slopes of less than 30 degrees. Concerning London, an environment strategy has been very recently adopted (Greater London Authority, 2018). It

plans the application of a Green space factor to secure a certain amount of green cover in every development. Such initiative represents a regulatory measure to promote green roofs. Finally, despite the presence of numerous historical buildings and individual houses covered by tiled and sloping roofs, Copenhagen and Amsterdam have succeed in having a better space coverage than Paris. When comparing these city-scale figures with national green roof implementation data, Paris seems to contradict the large-scale dynamics. While UK and Scandinavian countries are supposed to implement much less green roofs, their main cities are better covered by green roofs.

Conclusions and perspectives

For the first time, a fractal analysis has been conducted on the spatial distribution of green roof implementation in urban environment. For this purpose, geographical data synthetizing this information has been collected for 9 different European cities. By using a box-counting algorithm, 3 distinct scaling regimes have been defined when up-scaling the data from a 1-m resolution to an outer scale reaching several km. The second regime appears to be the most relevant to assess green roof implementation. Here the fractal dimension is the most variable, ranging from 0.50 to 1.35. The boundary of the scale range of this regime seems also to be an indicator of green roof size and distribution.

Such differences can be explained by several factors. Firstly, the architectural history of the city and the presence of buildings or individual houses characterized by sloped roofs than can make impossible the implementation of green roofs. Secondly, the greening policies (it is the case for 8 cities among the 9 studied ones) currently implemented in many urban areas -and its transposition in terms of

incentive subsidies or building regulations- should promote and facilitate their dissemination. It has to be noticed that the more ambitious incentive measures (where monetary subsidies are proposed) correspond to the cities characterized by the highest fractal dimension. As these policies are relatively recent, they cannot completely explain the current green roof distribution. They rather underline that an existing "greening culture" allow to better assimilate these policies (as a deadweight effect). Conversely, in country without such a culture, green roofs policies can appear too sophisticated and hinder architects to apply them.

Moreover, these policies are usually considered only at the building scale. As additional factors (social, performance, environment), they can contribute to drive designers and decision-makers in their choice (Rosasco and Perini, 2019). Concerning the environmental aspect, green roofs are expected to provide numerous ecosystem services: stormwater management by storing rain water (Versini et al., 2015), urban heat island mitigation by producing evapotranspiration (Santamouris, 2014), biodiversity protection by providing habitats (Madre et al., 2014), air quality improvement as passive filter (Baik et al., 2012)... An optimal source control stormwater management for instance requires a careful tuning of the green roofs -which are small storage capacities- distribution with the sewer network (which also exhibits fractal features). They have to be homogeneously implemented to avoid the concentration of impervious areas responsible for local flooding (Versini et al., 2016). Green corridors created to support biodiversity also need scale continuity between the different green features. Indeed, maintaining or restoring landscape connectivity is the most often

recommended measure to address the effect of climate change on biodiversity (Heller and Zavaleta, 2009), especially in urban areas (LaPoint et al., 2015). Green corridors enable species to move to more suitable locations.

To provide the mentioned ecosystem services at large scales, green roofs have to be widely and relevantly implemented. Fractal analysis can be seen as innovative multi-scale approach for this purpose. It can serve as a basis for evaluating potential impacts and producing optimized green roof deployment scenarios depending on the targeted impact(s). The fractal study presented in this paper demonstrates the irrelevance of density measurements that are scale dependent and unable to provide any information about the heterogeneity of green roofs spatial distribution. Fractal-based study appears also as an alternative to characterize the spatial organization - rather uniformly or in a contrasted way - of green roofs in urban environments, *a priori* perceived as shapeless. It represents a complementary tool to incentive policies (funding and/or regulation). It is therefore time to switch from a vegetalization conducted by local opportunities to a more reasoned one focused on its impacts at different space scales. By identifying the most sensible areas (flooding area, urban heat island,…), local authorities could start with greening all public buildings roofs (schools, hospitals, administrative offices…). Such initiatives could be a good signal for private investors and create a virtuous dynamic.

References

Ahrendt, J., 2007. Historische Gründächer: Ihr Entwicklungsgang bis zur Erfindung des Eisenbetons [Historical green roofs: Their development until the invention of the iron concrete]. Faculty VI of the TU Berlin.

Baik, J.-J., Kwak, K.-H., Park, S.-B., Ryu, Y.-H., 2012. Effects of building roof greening on air quality in street canyons. Atmos. Environ. 61, 48–55. https://doi.org/10.1016/j.atmosenv.2012.06.076
Benguigui, L., 1995. A Fractal Analysis of the Public Transportation System of Paris. Environ. Plan. A 27, 1147–1161. https://doi.org/10.1068/a271147
Coenradie, B., Haag, L., 2016. Erhebung und Aufbereitung von Informationen zum Gründachbestand in Berlin [Acquisition and processing of data on the stock of green roofs in Berlin], Senate Department for Urban Development and the Environment (ed.).
Cook-Patton, S.C., Bauerle, T.L., 2012. Potential benefits of plant diversity on vegetated roofs: A literature review. J. Environ. Manage. 106, 85–92. https://doi.org/10.1016/j.jenvman.2012.04.003
Dupuy, G. (Ed.), 2017. Villes, réseaux et transport: le défi fractal, Méthodes et approches. Economica, Paris.
European Commission, 2016. Supporting the implementation of Green Infrastructure. European Commission,Directorate-General for the Environment.
Feng, J., Chen, Y., 2010. Spatiotemporal evolution of urban form and land-use structure in Hangzhou, China: evidence from fractals. Environ. Plan. B Plan. Des. 37, 838–856. https://doi.org/10.1068/b35078
Francis, L.F.M., Jensen, M.B., 2017. Benefits of green roofs: A systematic review of the evidence for three ecosystem services. Urban For. Urban Green. 28, 167–176. https://doi.org/10.1016/j.ufug.2017.10.015
Frankhauser, P., 2004. Comparing the morphology of urban patterns in Europe – a fractal approach, in: European Cities – Insights on Outskirts, Report COST Action 10 Urban Civil Engineering. Brussels, pp. 79–105.
Gires, A., Tchiguirinskaia, I., Schertzer, D., Ochoa-Rodriguez, S., Willems, P., Ichiba, A., Wang, L.-P., Pina, R., Van Assel, J., Bruni, G., Murla Tuyls, D., ten Veldhuis, M.-C., 2017. Fractal analysis of urban catchments and their representation in semi-distributed models: imperviousness and sewer system. Hydrol. Earth Syst. Sci. 21, 2361–2375. https://doi.org/10.5194/hess-21-2361-2017
Greater London Authority, 2018. London Environment Strategy.
Heller, N.E., Zavaleta, E.S., 2009. Biodiversity management in the face of climate change: A review of 22 years of recommendations. Biol. Conserv. 142, 14–32. https://doi.org/10.1016/j.biocon.2008.10.006
Hentschel, H.G.E., Procaccia, I., 1983. The infinite number of generalized dimensions of fractals and strange attractors. Phys. Nonlinear Phenom. 8, 435–444. https://doi.org/10.1016/0167-2789(83)90235-X
LaPoint, S., Balkenhol, N., Hale, J., Sadler, J., van der Ree, R., 2015. Ecological connectivity research in urban areas. Funct. Ecol. 29, 868–878. https://doi.org/10.1111/1365-2435.12489
Lovejoy, S., Schertzer, D., Ladoy, P., 1986. Fractal characterization of inhomogeneous geophysical measuring networks. Nature 319, 43–44. https://doi.org/10.1038/319043a0
Lovejoy, S., Schertzer, D., Tsonis, A.A., 1987a. Functional Box-Counting and Multiple Elliptical Dimensions in Rain. Science 235, 1036–1038. https://doi.org/10.1126/science.235.4792.1036

Lovejoy, S., Schertzer, D., Tsonis, A.A., 1987b. Functional Box-Counting and Multiple Elliptical Dimensions in Rain. Science 235, 1036–1038. https://doi.org/10.1126/science.235.4792.1036
Madre, F., Vergnes, A., Machon, N., Clergeau, P., 2014. Green roofs as habitats for wild plant species in urban landscapes: First insights from a large-scale sampling. Landsc. Urban Plan. 122, 100–107. https://doi.org/10.1016/j.landurbplan.2013.11.012
Mandelbrot, B.B., 1983. The fractal geometry of nature, Updated and augmented. ed. Freeman, New York, NY.
Oberndorfer, E., Lundholm, J., Bass, B., Coffman, R.R., Doshi, H., Dunnett, N., Gaffin, S., Köhler, M., Liu, K.K.Y., Rowe, B., 2007. Green Roofs as Urban Ecosystems: Ecological Structures, Functions, and Services. BioScience 57, 823–833. https://doi.org/10.1641/B571005
Rosasco, P., Perini, K., 2019. Selection of (Green) Roof Systems: A Sustainability-Based Multi-Criteria Analysis. Buildings 9, 134. https://doi.org/10.3390/buildings9050134
Santamouris, M., 2014. Cooling the cities – A review of reflective and green roof mitigation technologies to fight heat island and improve comfort in urban environments. Sol. Energy 103, 682–703. https://doi.org/10.1016/j.solener.2012.07.003
Schertzer, D., Lovejoy, S., 1987. Physical modeling and analysis of rain and clouds by anisotropic scaling multiplicative processes. J. Geophys. Res. 92, 9693. https://doi.org/10.1029/JD092iD08p09693
Speak, A.F., Rothwell, J.J., Lindley, S.J., Smith, C.L., 2012. Urban particulate pollution reduction by four species of green roof vegetation in a UK city. Atmos. Environ. 61, 283–293. https://doi.org/10.1016/j.atmosenv.2012.07.043
Stovin, V., Vesuviano, G., Kasmin, H., 2012. The hydrological performance of a green roof test bed under UK climatic conditions. J. Hydrol. 414–415, 148–161. https://doi.org/10.1016/j.jhydrol.2011.10.022
Suter, I., Maksimović, Č., van Reeuwijk, M., 2017. A neighbourhood-scale estimate for the cooling potential of green roofs. Urban Clim. 20, 33–45. https://doi.org/10.1016/j.uclim.2017.02.007
Versini, P.-A., Gires, A., Tchinguirinskaia, I., Schertzer, D., 2016. Toward an operational tool to simulate green roof hydrological impact at the basin scale: a new version of the distributed rainfall-runoff model Multi-Hydro. Water Sci. Technol. 74, 1845–1854. https://doi.org/10.2166/wst.2016.310
Versini, P.-A., Jouve, P., Ramier, D., Berthier, E., de Gouvello, B., 2015. Use of green roofs to solve storm water issues at the basin scale – Study in the Hauts-de-Seine County (France). Urban Water J. 1–10. https://doi.org/10.1080/1573062X.2014.993993

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