How complexity in vegetation structure and distance from the ground-level habitat influence spontaneous plant diversity on green-roofs

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MSc Thesis

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In loving memory of Camicia, she would have loved green-roofs so much.

To Mamma, Papà, Ale, Vale, Caro, and Angelo, who supported me, believed in me, and were my ‘home’ through all this journey.

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Abstract

The urbanisation pressure on biodiversity is in constant rise, affecting also urban green-spaces. Urban green-spaces can mitigate habitat fragmentation, yet these are challenging to manage in dense urban areas. Green-roofs can be an answer to this issue, thanks to their habitat connectivity properties. In fact, green-roofs can host spontaneous plants, which are usually native, meaning that they can support habitat connectivity also for local fauna. In order to understand what environmental parameters have the most significant effect on spontaneous plant species establishment, this research compared green-roofs with natural ecosystem dynamics. Vegetation structure relates to species diversity in natural habitats, and to ecosystem resilience. This relationship is the foundation of the habitat heterogeneity hypothesis, the theoretical base of this study. So, the effects of the surrounding areas, the technical and spatial characteristics of the green-roofs, and the vegetation were investigated. Particularly, this research focused on (a) the effect of distance from the ground-level habitat (intended as city parks and nature areas included in Amsterdam Nature Network), and (b) the structure of the planted vegetation. A total of 38 green-roofs, located in the city of Amsterdam, were systematically sampled and analysed to answer the two research questions (a,b). (a) Firstly, spontaneous plant species diversity is not significantly influenced by the distance from the ground-level habitat, meaning that the diversity of spontaneous plant species does not increase in the proximity of ground-level habitats. So, this effect can be considered marginally. This allows to shift the focus on the effect of local environmental variables, such as vegetation structure. (b) Secondly, spontaneous plant species diversity presents a positive relationship with vegetation structure complexity, intended as a combination of vertical and horizontal structure of the vegetation. This relationship is even stronger when the green-roof age is considered an influential parameter, so older green-roofs with a more complex structure of the vegetation present higher spontaneous species diversity. Yet, also vertical and horizontal structure show a positive relationship with spontaneous plants species diversity, hence supporting the habitat heterogeneity hypothesis validity on green-roof vegetation.

These research findings can contribute to build ecological knowledge about green-roofs, which is fundamental to achieve an optimal management strategy, and to take advantage of all the potential benefits of green-roofs.

1. Introduction

By 2050, 68% of the human population is expected to live in cities (UN, 2018), resulting in the expansion of cities worldwide. The rapid urbanisation process represents a significant pressure on natural resources and biodiversity (Seto et al., 2013). Built areas already account for more than 30% of the greenhouse emission globally (Berardi et al., 2014), and there is demand for further urban development. Urbanisation negatively affects urban green spaces (Zhou & Wang, 2011), which are important for human wellbeing (Bertram & Rehdanz, 2015). In fact, urban green spaces improve urban climate, with consequent environmental, social and economical benefits (Heidt & Neef, 2008). Furthermore, urban green spaces are important to preserve in order to mitigate habitat fragmentation and support biodiversity (Jongman, 2008; Breuste et al., 2013; Kim & Pauleit, 2007). The management and planning of urban green-spaces can be particularly challenging in areas where urban densification processes take place (Haaland & van Den Bosch, 2015). An interesting option to provide green space in dense urban environments is green-roofs (Haaland & van Den Bosch, 2015), which are ecosystems placed on top of buildings. Green-roofs can be defined as small-scale, simple, and human-made ecosystems (Sutton, 2015). Nowadays, green-roofs can be frequently seen in cities (Williams et al., 2014), and they are often included in urban development policies because of their environmental, aesthetic, and economic benefits (Oberndorfer et al., 2007). Green-roofs can provide benefits generally associated with ground-level nature, such as mitigation of urban heat island effect, noise reduction (MEA, 2005), or stormwater retention (Dietz & Clausen, 2006). Amongst these benefits, they can also serve as habitat for local biodiversity (MEA, 2005; Brenneisen, 2006), for instance through the provision of habitat for rare or endangered species under urbanisation pressures (Brenneisen, 2006), and in terms of ecological restoration and conservation of local declining plant species with adaptive traits (Rosenzweig, 2003; Francis & Lorimer, 2011).

Hence, since green-roofs deliver similar benefits to natural ecosystems and they are actually conceived to imitate them (Oberndorfer et al., 2007), it is interesting to observe what natural ecosystem dynamics can be also associated with green-roofs, such as biodiversity and vegetation structure.

1.1 Vegetation structure and its link to biodiversity

Vegetation structure and species diversity are both essential elements for assuring ecosystems resilience (Elmqvist et al., 2003; Dorren et al., 2004). Vegetation structure relates to the habitat availability and to the successional stage of a certain ecosystem (Jones et al., 2004; Silver et al., 2004; Wang et al., 2004). A higher complexity of the vegetation structure can facilitate biotic colonisation locally (Ruiz-Jaén & Aide, 2005) since more 'niches' are created allowing more species to establish (Bergen et al., 2009).

Vegetation structure can be defined from different viewpoints, for instance considering the horizontal (spatial) and vertical (stratification) structures. These can both relate to biodiversity (Haila, 1999; Brokaw and Lent, 1999), including flora and fauna (Lindenmayer et al., 2000).

The relationship between foliage-height diversity (or vertical vegetation structure) and species diversity (McArthur & McArthur, 1961) is the foundational hypothesis for successive research about vegetation structure and biodiversity. Particularly, plant diversity appears to relate to vegetation structure, since vertical stratification creates differentiated habitat conditions, allowing for colonisation of plant species (Gao et al., 2014). Interestingly, studies on different types of landscapes, supported vegetation diversity as the best predictor for general biodiversity (Simonson et al., 2001; Sauberer et al., 2004; Bräuniger et al., 2010). Consequently, both vegetation structure and plant species diversity can be useful parameters for monitoring the biodiversity dynamics of an ecosystem, thus its resilience. Yet, the necessary data are often unavailable for a lack of species inventory accuracy (Gao et al., 2014). Furthermore, even though there surely is a linkage between vegetation structure and biodiversity at all scales (Tews et al., 2004), the most consistent relationships are shown at relatively small scales (Bergen et al., 2009). So, since in natural ecosystems the connection among vegetation structure, vegetation biodiversity, and fauna and flora biodiversity, is mostly tangible at small scales, it can be possible to project these processes and relationships on green-roof ecosystems. These are, in fact, small-scale ecosystems, and such comparison can be interesting for understanding green-roof ecosystem dynamics, particularly biodiversity dynamics.

1.2 Green-roofs can support biodiversity in cities

All the environmental benefits provided by green-roofs are associated with their ecosystem-like functioning (Oberndorfer et al., 2007). A relevant characteristic of green-roofs, is that they are based on the biomimicry and bioengineering concepts, thus they are thought to mimic natural ecosystems in order to provide similar benefits (Oberndorfer et al., 2007), so there is a range of possibilities to manipulate green-roof characteristics in order to obtain selected benefits.
In the context of this research (spontaneous) species diversity is considered an indicator of the green-roof health state since, in natural ecosystems, it is strictly connected to vegetation structure and ecosystem resilience (*1.1*). Yet, there are parameters that can possibly influence spontaneous species diversity, such as distance from ground-level habitat and, the aforementioned, vegetation structure.

Firstly, since green-roofs can provide habitat connectivity for spontaneous plant species populations (Dunnett et al., 2008), the characteristics of the surrounding ground level habitats and their distance from the green-roof can be relevant factors. On the one hand, to the best of my knowledge, research solely focused on the effect of the surrounding ground level habitats on green-roofs spontaneous vegetation has not been carried out. On the other hand, it is considered amongst the possible influential variables on spontaneous species diversity on green-roofs by Madre et al. (2014), together with substrate depth, green-roof surface, building height, green-roof age, and maintenance intensity. Substrate depth, and other characteristics at the green-roof scale, such as a higher diversity in biological communities (Balvanera et al., 2006; Cardinale et al., 2006; Vandermeer et al., 2002), can be managed in order to enhance green-roofs ecosystem services and other processes.

Secondly, amongst the various options for enhancing biological diversity on green-roofs, there is habitat heterogeneity, which seems to support biodiversity through the provision of more diverse microhabitats (Lundholm & Heim, 2020). Current research is examining the potential of habitat heterogeneity for supporting biodiversity on green-roofs (Buffman & Starry, 2020), with interesting results in the context of light environment and soil humidity variations (Heim & Lundholm, 2020; Holloway et al., 2020; Li et al., 2020). *Biotic* *heterogeneity*, meant as the microhabitat variations caused by living organisms (Lundholm & Heim, 2020), can influence temperature, nutrients, and other conditions (Lundholm, 2016). In this context, vegetation structure is intended as *biotic heterogeneity* in Heim & Lundholm (2020), which also causes variations in light environment and humidity, thus it may have interesting effects on local plant biodiversity.

Finally, it is important to illustrate how spontaneous plants are relevant for biodiversity and nature conservation. Spontaneous vegetation is defined as the plant species which were not planted in the installation phase of the green-roof. Wild or spontaneous plants can establish on green-roofs (Dunnet et al., 2008), and become an integrated part of green-roof ecosystems. In fact, besides the fundamental trophic function of vegetation in general, spontaneous plants are particularly appropriate hosts for urban faunal diversity (Madre et al., 2014), including pollinators, since they are mostly native plant species (Tonietto et al., 2011).

Therefore, green-roof ecosystems made of a more complex assemblage of living organisms can provide a wider range of microhabitats for local biodiversity. From the vegetation point of view, this complexity can, for example, be looked at in terms of vegetation structure. Research in several fields of study relates green-roofs to natural ecosystems (Sutton, 2015). Therefore, it is relevant to consider natural ecosystem dynamics, which can be observed and tested on green-roofs, such as vegetation structure and plant biodiversity.

In this perspective, an interesting research focus is presented in Madre et al. (2014). In that research, vegetation structure, as ecological typology, is related to local biodiversity establishment on green-roofs. Yet, it highlights the role of substrate depth, not considering vegetation structure a possible influential variable. Along these lines, the aim of this research is to verify the effect of vegetation structure complexity on local biodiversity establishment, through the monitoring of spontaneous species on selected green-roofs in Amsterdam. Furthermore, other possible influential parameters are going to be monitored, particularly the distance of green-roofs from ground-level habitats, but also green-roof age, building height, soil depth, green-roof surface, and maintenance intensity (Madre et al., 2014).

1.3 Research objectives, questions, and hypotheses

The main research question leading this thesis research is:

Is the spontaneous plant species diversity on green-roofs influenced by the distance from ground-level habitat, and by the structural complexity of the planted vegetation on the green-roof?

Two sub-questions have been extrapolated, in order to guide the operationalisation of the underpinning concepts in an empirical context: these focus respectively on (a) the distance from ground-level habitat, and on (b) the structural complexity of the planted vegetation.

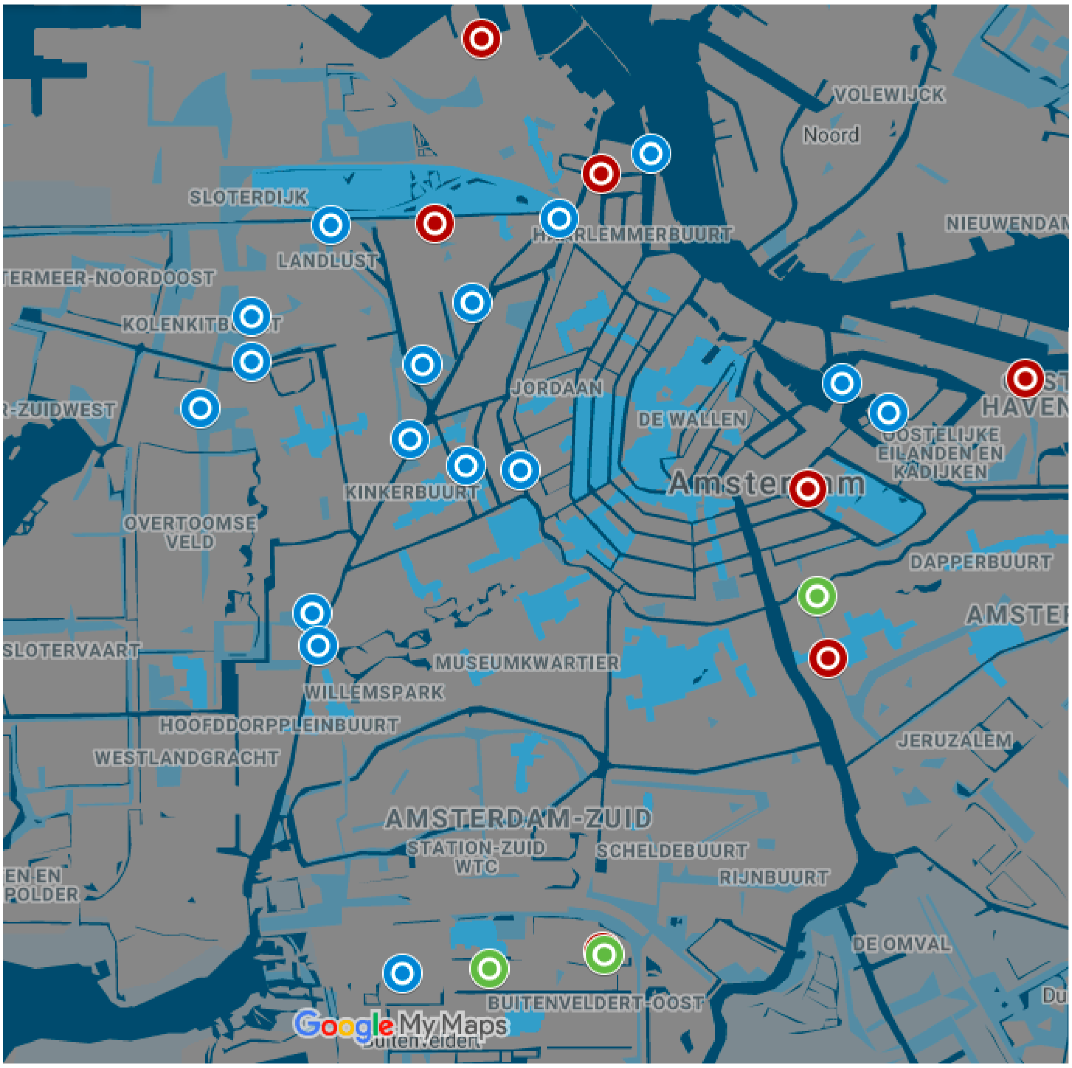
In this study, *spontaneous vegetation* is defined as the plant species recorded through the data collection (t=1) which were not planted in the installation phase of the green-roof (t=0).

The distance of ground-level habitats from green-roofs is expected to have a negative influence on the spontaneous plants' establishment and diversity (*hypothesis a*; Madre et al., 2014). However, vegetation structure is expected to have the most significant impact on spontaneous plants establishment and biodiversity *(hypothesis b)*. This is based on the fact that vegetation structure complexity can be considered a form of habitat heterogeneity, in terms of biotic heterogeneity (Lundholm & Heim, 2020). So, the plants themselves create local variations in temperature, nutrients, light, and other environmental conditions, which creates additional niches for plant biodiversity (Lundholm, 2016; Gao et al., 2014).

2. Materials and methods

2.1 Study area

The selected study areas were 38 green-roofs situated in Amsterdam, heterogeneously distributed through the city (**FIG. 2.1.1**).



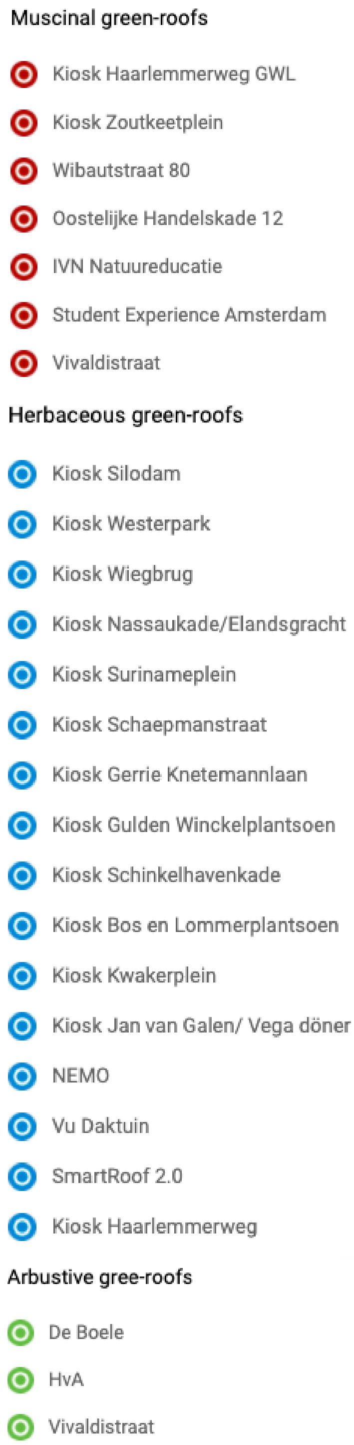


FIGURE 2.1.1 Green-roofs selected for this research. Different types of roofs are represented in different colors: (red) muscinal (or Sedum) green-roofs, (blue) herbaceous green-roofs, (green) arbustive green-roofs (or roof-gardens). Map accessible on: https://www.google.com/maps/d/edit?mid=10IhCTi5_NhyiypXY745nqWT89YUvjFUb&usp=sharing

The green-roofs selection was based on accessibility constraints and research requirements. The requirements for the selected roofs were: (1) located in the municipality of Amsterdam, (2) maximum building height 30 m, (3) age between 2 and 15 years old, (4) accessible in spring 2021, (5) muscinal, herbaceous, arbustive or arboreous vegetation structure (**FIG. 2.1.2**). The selected green-roofs presented different characteristics.

First, 15 of the selected green-roofs (*kiosk roofs*) presented similar characteristics with different locations, and 11 similar green-roofs (*Student experience*) were situated on the same building at different heights, thus these roofs had a variable distance from ground-level habitats. These two groups of green-roofs were analysed to answer the research question (a).

Secondly, the selected green-roofs presented different structures of the planted vegetation (sedum, herbs, grasses, shrubs, small trees) and were classified and researched accordingly (muscinal, herbaceous, arbustive, arboreous). These groups of green-roofs, together with the kiosks, and three sample Student Experience green-roofs, were analysed to answer the research question (b).

Thirdly, two of the selected green-roofs (*NU-VU, SmartRoof 2.0*) presented heterogeneous vegetation structure of the planted vegetation and a more complex spontaneous vegetation distribution. These two green-roofs were observed and inventoried as case studies, in order to support the discussion of the research question (b). These differences in the green-roofs characteristics were taken into account to choose a suitable sampling strategy (*2.2*), and data analysis (*2.4*).

It is also important to mention that the meteorological conditions throughout all the fieldwork period were very often rainy and relatively cold for the season.

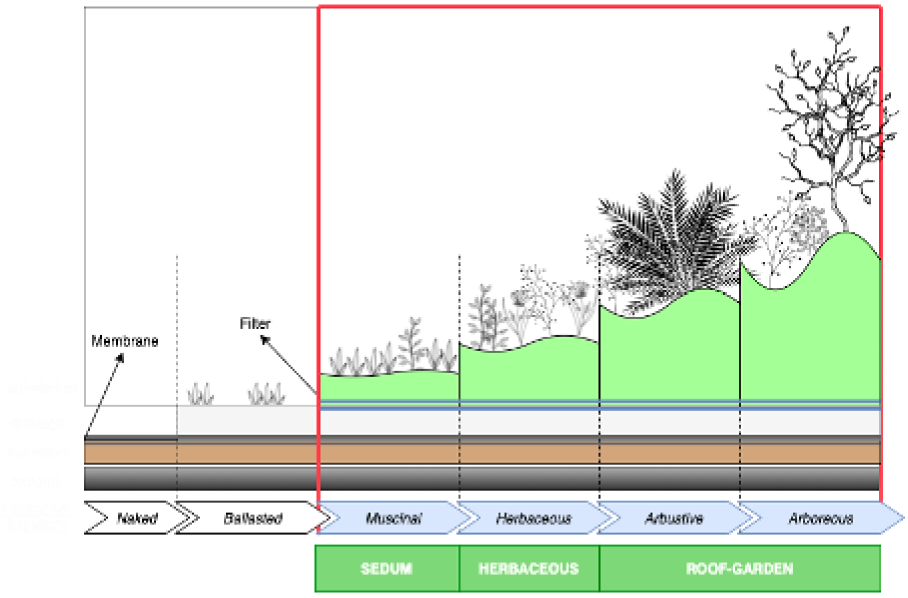


FIGURE 2.1.2 Green-roofs can be classified by the ecological typologies classification by Bournérias (1968). The focus of this research is on the differences among muscinal (or Sedum), herbaceous, arbustive and arboreous (or roof gardens) green-roofs in terms of their biodiversity support function.

2.2 Sampling design

The data collection consisted of a single fieldwork round, during the peak of the vegetative season, between May and July 2021. Data about the *surroundings*, *green-roof characteristics,* and *vegetation structure* were collected (*2.3*, **TAB.. 2.3.1**). Information about the maintenance operations applied through the year, the list of planted species, and the *green-roof characteristics* (*2.3*) were requested to the green-roof owner or maintenance company, or estimated based on observations during the site visits.

To sum up, the measurement of the vertical and horizontal vegetation structure, plus a vegetation analysis, were carried out for all the green-roofs. While the analysis of the surroundings, only interested the kiosks and the Student Experience green-roofs.
So, the measurements and parameters considered during this research changed according to the purpose of the different groups of green-roofs analysed. The vegetation sampling was done following a similar protocol on the majority of the green-roofs, except for the heterogeneous ones (VU Daktuin, SmartRoof 2.0).

All the green-roofs
Firstly, the general information about the green-roof was recorded. For each green-roof, the *vertical* and *horizontal structure* of the vegetation (*2.3*) were determined through visual observations and simple measurements.
Secondly, a more detailed analysis of the vegetation was carried out. All the green-roofs were sampled using a systematic sampling strategy. For each roof, three circular sample areas (⌧ = 1 m) were selected, placed on the diagonal of the green-roof, and as far as possible from the edges (**FIG. 2.2.1**). Within the sample areas, the vegetation was inventoried, including a visual estimate of the cover percentage per species observed. The species identification was required to distinguish the spontaneous plants from the planted vegetation

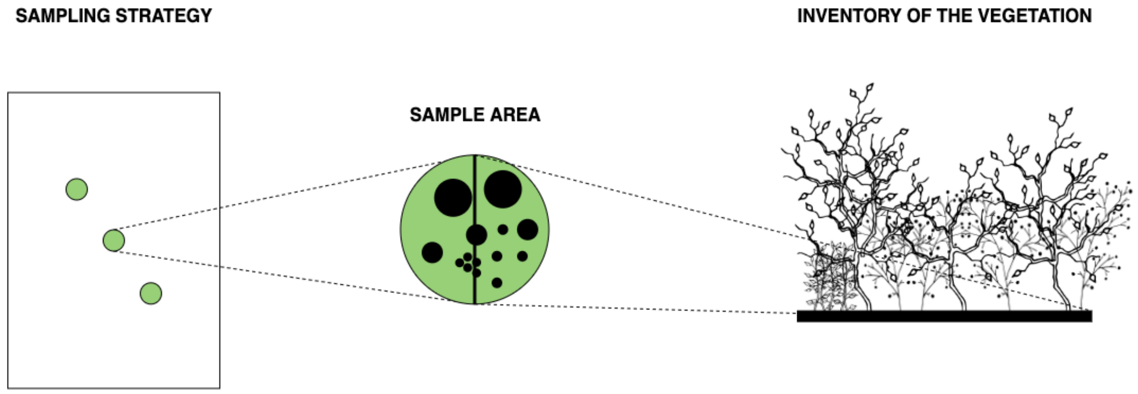


FIGURE 2.2.1 Systematic sampling, with 3 sample areas, was applied on all the roofs (*SAMPLING STRATEGY*), except for heterogeneous roofs, where all the vegetation was inventoried.

Heterogeneous green-roofs
The vegetation on the heterogeneous green-roofs (*VU Daktuin, SmartRoof 2.0*), instead, was fully inventoried.

Student Experience and Kiosk green-roofs
Differently from the vegetation sampling, the study of the surroundings interested only the 26 green-roofs (*kiosks* and *Student Experience*), designated for studying the effects on spontaneous species diversity of the distance from ground-level habitats.
In order to study the surrounding areas, the possible ground-level habitats within a range

(~300 m) from these green-roofs were mapped on GIS. Furthermore, also the distance of each of these green-roofs from the closest *ecological hub*, defined as any green area included in the Amsterdam Nature Network (Gemeente Amsterdam Klaas-Bindert de Haan, n.d.), was calculated.

2.3 Variables and measurements

First, the data collected about each green-roof was divided into 3 groups, from the biggest to the smallest scale, (1) *surroundings*, (2) *green-roof characteristics,* and (3) *vegetation* (**FIG. 2.3.1, TAB. 2.3.1**).

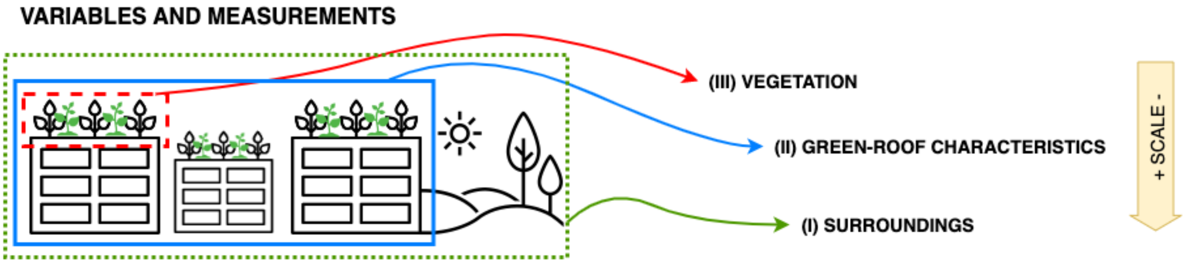


FIGURE 2.3.1 Visual representation of the degree of detail given by measured and given variables included in this research, based on the scale these refer to.

TABLE 2.3.1 *'Variables taken into account or measured on the field'*. (*)

groups	*variables*	*RQ(a)*	*RQ(b)*

I. SURROUNDINGS	environment surrounding the green-roofs:
	• building height [m]
	• distance from ground-level habitat [m]
	  ○ diagonal/Pythagorean distance from ground-level habitat [m]
	• distance from closest ecological-hub [m]
	  ○ diagonal/Pythagorean distance from closest eco-hub [m]
	• degree of urbanisation of the surroundings [%]		

II. GREEN-ROOF CHARACTERISTICS	<u>structural and spatial characteristics:</u> • green-roof age [years] • green roof surface [m2] • soil depth [mm] • maintenance [0,1, 2, 3] • green-roof or blue-green-roof [0,1] <u>temperature loggers (kiosks):</u> • minimum temperature [°C] • maximum temperature [°C] • average temperature [°C] • ∆ temperatures [° C] • shading index [0,1,2,3]		

III. VEGETATION	<u>vertical vegetation structure:</u>
	• plants height [m]
	  ○ maximum
	  ○ average
	• stratification [number of layers]
	  ○ maximum
	  ○ average
	<u>horizontal vegetation structure:</u>
	• ecological typology		

	[muscinal, herbaceous, arbustive] ○ muscinal cover [%] ○ herbaceous cover [%] ○ arbustive cover [%] planted and spontaneous vegetation: ● species composition [species a, …, species n] ● species cover [%] ● planted or spontaneous [P,S]		

(*) Several variables were taken into account or measured on the field. These variables can be divided into 3 big groups, and sorted by the scale to which they refer as green-roof descriptors. The corresponding research question(s) are indicated in light-blue.

Surroundings of the green-roof

The data included in (I) *surroundings* provide a description of the environment surrounding the green-roofs which are the object of this research. The descriptors chosen for the surroundings are (a) *building height [m]*, (b) *distance from ground-level habitat* [m], (c) *distance from the closest ecological hub* [m], and (d) *degree of urbanisation of the surroundings* [%]. The diagonal distances from habitat were also calculated.

Green-roof characteristics

The (II) *green-roof characteristics* regard all the structural and spatial characteristics of the green-roof habitats on a macro-scale. These are (a) *green-roof age [years]*, (b) *green roof surface [m2]*, (c) *soil depth [mm]*, (d) *maintenance [0,1, 2, 3]*, (e) *green-roof or blue-green-roof [0,1]*.
An indicator for considering the maintenance intensity was set on a scale from 0 to 4, from the lower to the higher level of maintenance. '*0'* corresponds to no maintenance operations applied on the green-roof, and '*4'* corresponds to repeated maintenance rounds (up to 4) per year, which include intensive weeding and supplementary irrigation.
Additionally, iButton one-wire data loggers were placed in the middle of the kiosk green-roofs, to detect and record the temperatures of 4 sample days. Thus, (f) *minimum,* (g) *maximum,* (h) *average,* and (i) ∆ *temperatures* were taken into account, additionally to a (j) *shading index [0,1,2,3]*. The shading index was specified with a score, that is 0 for 'no shade', 1 for 'building shade', 2 for 'building and vegetation shade', and 3 for 'vegetation shade'. The data about the (II) *green-roof characteristics* were requested from the green-roof owner or maintenance company, or they will be assessed in the field.

Vegetation sampling

The data included in (III) *vegetation* are divided into *(a) vertical structure* and *(b) horizontal structure*, which were determined through on-site visual observations.
Firstly, the *(a) vertical structure* was measured in terms of *foliage-height diversity* (McArthur and McArthur, 1961), a measure of the vertical vegetation structure, which considers the number of vertical foliage layers present in a given point of a plot, as an estimate of vertical stratification. The index was simplified according to the purpose, so *plants height [m]* (maximum and average) and *stratification [n]* (maximum and average) were measured per each green-roof.
Secondly, on the one hand, the *(b) horizontal structure* was generally defined by a vegetation category or *ecological typology* (Bournérias, 1968), characterising each green-roof. This classification described vegetation according to its upper stratum, meant as the layer of most complex vegetation growth form, accounting for at least 20% of the vegetation cover (**FIG. 2.1.2**). This classification was applied to green-roofs in past research (e.g. Madre

et al., 2014). The dominant stratum was defined as *"muscinal"* when composed of bryophytes, lichens, and fungi and also small herbaceous plants, such as creeping succulents (e.g. Sedum), as *"herbaceous"* when dominated by such non-woody herbaceous plants as grasses, and flowering plants that can exceed 1m in height at maturity, as *"arbustive"* when characterised by shrubs, bushes, and young trees (from 1 to 7 m high), or as *"arboreous"* with the presence of large trees, (over 7m) (Bournérias, 1968). Thus, the dominant stratum label defines the ecological typology of the whole green-roof.
On the other hand, since the ecological typology of each green-roof is based on the *cover percentage [%]* of *muscinal, herbaceous, arbustive, and arboreous plants*, these measures of cover percentage can be seen as the descriptive components of the horizontal vegetation structure, on a more detailed level.
Lastly, the *species composition [spp.]* and *cover percentage per species [%]* were measured within the sample areas and then standardised to the whole green-roof. The inventory and identification of the species were necessary to facilitate the distinction between planted and spontaneous vegetation. The cover percentage per species, instead, allowed to determine the *Shannon-Wiener Index of diversity*. This index, which takes into account both species abundance and richness, was calculated for the spontaneous plant species of each green-roof analysed. Furthermore, the γ-diversity was also determined to have an overview of the overall Amsterdam green-roofs plant diversity.

2.4 Data analysis

In order to better understand the relationships studied and answer the research questions (a,b), four different datasets were created: the (1) Student Experience, including 13 green-roofs on the Student Experience building, the (2) Kiosks, including 15 kiosk green-roofs, the (3) green-roofs dataset, including the other green-roofs, together with the kiosks and three sample Student Experience green-roofs, and the (4) species database, including a list of all the plant species identified through this research on all the green-roofs analysed. Building four different datasets was meant to organise the data (datasets 1,2,4 to answer the research question a; datasets 3,4 to answer the research question b), thus facilitating the analysis.
As a starting point, several exploratory analysis were carried out on the datasets (1,2,3). Correlation matrixes were run on all these datasets, to verify possible correlation bias, plus an explorative PCA was applied to the datasets (2,3).
Additionally, when models were created, the relationships between the single independent variables and the dependent variable were plotted through simple data visualisation for clarification.
However, the most considerable part of the data analysis concerned creating several Linear Models (LM), and Generalised Linear Models (GLM), including the significant or interesting variables highlighted in the exploratory phase. Successively, these LMs and GLMs were tested and compared with ANOVA, in order to select the more suitable ones to answer my research questions. More details about these statistical models are discussed in the following chapters.
Lastly, the dataset (4), was at the base of the important preliminary step of sorting out the plant species recorded.

2.4.1 Plant species analysis

The plant species recorded through the data collection were analysed in a separate database (4). First identified, and then classified as spontaneous or planted, the species counted in the three sample areas per green-roof were added-up. Successively, considering the cover percentage of each species as an approximate number of individuals, the Shannon Index of Diversity and the Simpson Index were calculated for the spontaneous species. Additionally, the γ-diversity was calculated, and the most common spontaneous species were ranked.

2.4.2 Research question a: Distance from habitat

The first research objective was to verify the effect of distance from habitat (independent variable) on the spontaneous plant species diversity (dependent variable). The distance from habitat was measured considering different perspectives, conceptually and analytically. Also, the green areas surrounding the green-roofs were analysed in order to understand if they could have any relationship with spontaneous plant species diversity.

Firstly, the Student Experience green-roofs (1) were analysed applying two LMs, to test the effect of the height variation on the spontaneous species diversity. One LM took into account the building height, and the other one considered the Pythagorean distance from the closest eco-hub (as $\sqrt{\text{building height^2+distance from the closest eco-hub^2}}$). The models were then compared with an ANOVA test.

Secondly, the Kiosks (2) were analysed in terms of their distance from the closest eco-hub. Both the ground-level distance and the Pythagorean distance from the closest eco-hub were tested through LMs and compared with an ANOVA.

2.4.3 Research question b: Vegetation structure

The second research objective implied the investigation of the effect of vegetation structure (independent variable) on the spontaneous plant species diversity (dependent variable). Also, the concept of *vegetation structure* was explored in different interpretations.
On the one hand, the combined effect of vertical and horizontal vegetation structure was examined. On the other hand, the vegetation structure was considered separating the effects of vertical and horizontal structure (as they are defined in **TAB. 2.3.1**).

Firstly, the analysis was applied to the Kiosk green-roofs (2). Since these appeared to have more standardised green-roof characteristics (*II*, **TAB. 2.3.1**) than the rest of the green-roofs, the focus of this stage of the analysis could stay only on the various parameters describing the vegetation structure (*III*, **TAB. 2.3.1**). A GLM was applied to this dataset to analyse the data. Successively, a more detailed analysis was carried out to understand the different effects of vertical and horizontal structure, building two distinct GLMs.
Also, the surroundings (*I*, **TAB. 2.3.1**) concerning the Kiosks (2) were tested again, this time including the *temperature loggers* data (*II*, **TAB. 2.3.1**), building another GLM. Then this GLM about the Kiosks' surroundings was compared to the GLMs including the vegetation structure, vertical structure, and horizontal structure.

Secondly, on the Green-roofs dataset (3) was applied a similar analytical procedure. Similarly, vegetation structure (vertical+horizontal), vertical structure, and horizontal structure were analysed building three GLMs. Additionally, the relationships between each variable describing vegetation structure (*III*, **TAB. 2.3.1**) and spontaneous plant species diversity was examined.
Yet, in the Green-roofs dataset (3) there was a variation of green-roof characteristics (*II*, **Table 2.3.1**), besides the surroundings (*I*, **TAB. 2.3.1**). Thus, these two groups of variables were analysed, in terms of their relationship with spontaneous plant species diversity, building two distinct GLMs. Finally, all the GLMs built for analysing the dataset (3) were compared through an ANOVA test.

3. Results and discussion

The distance from habitat of green-roofs, addressed by the first research question, seems to have a minor effect on spontaneous plant species diversity.
In contrast, the vegetation structure, targeted by the second research question, shows a significant influence on spontaneous plant species diversity from different points of view. These results, and other secondary findings, are discussed in the following chapters.

3.1 Distance from habitat has a minor influence on plant species diversity

«Is the spontaneous plant species diversity on green-roofs influenced by the distance from the ground-level habitat?»

The verification of the effect of the distance from habitat, observing various definitions of it, was an important stage of this research. Since the relationship of these variables with spontaneous plant species diversity is not particularly meaningful, its effect can be considered marginally in the following analysis phases, and in the discussion of the results. This allows focusing on a smaller scale, considering and examining the effect of local environmental variables, such as vegetation structure.

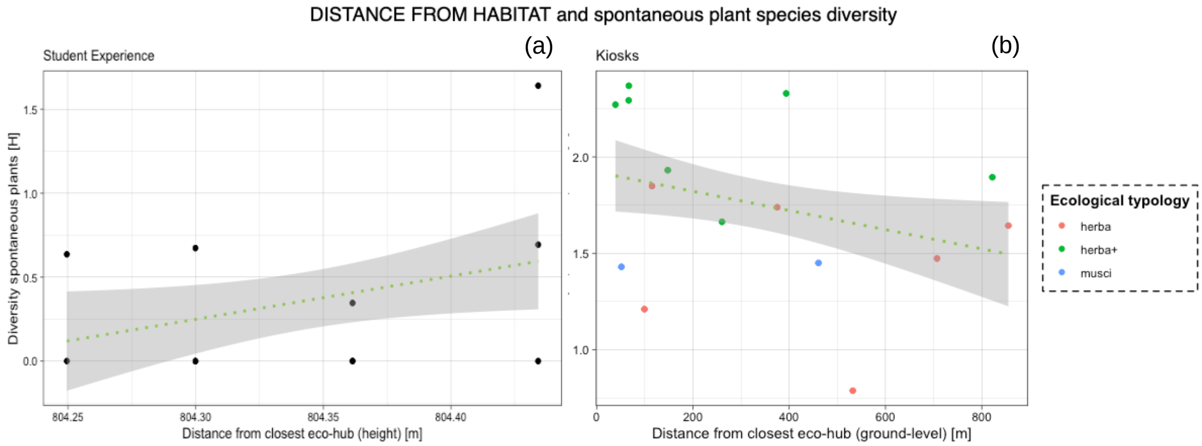


FIGURE 3.1.1. (a) The study of the effect of the building height on spontaneous plant species diversity is applied to the Student Experience green-roofs. The plot shows a slightly positive relationship between diagonal distance from closest eco-hub and spontaneous species diversity, meaning that the higher the green-roof is located, the higher the diversity of spontaneous species is, which is not consistent from an ecological point of view. **(b)** The graph showing the study carried out on the kiosks, characterised by varying distances from the closest eco-hub, displays a slightly negative relationship with spontaneous plant species diversity. This means that the closer the green-roof is to a ground-level eco-hub, the higher the spontaneous species diversity is. This is aligned with the predicted ecological response.

The most significant effect of the surroundings (**TAB. 2.3.1**, *I*) is defined by the *building height*, and as the *distance from the closest eco-hub*.

First, the Student Experience roofs were analysed to determine the effect of *building height [m]* on *spontaneous plant species diversity*.
As a representative measure of the building height, the Pythagorean distance from the ground-level habitat (2.4.2) showed the most significant relationship with spontaneous plant species diversity. However, this relationship was very weak (LM: adjusted R-squared value of 0,09165), and the highest diversity was found on the highest roof, not the lowest roof as expected (**FIG. 3.1.1a**). It has to be considered that the Student Experience green-roofs are young (1,5 year old), and highly maintained. Weeding operations were applied only a few weeks previous to the data collection, and this might have had an impact on spontaneous plant species diversity on these green-roofs.
Yet, in terms of vegetation structure, the Student Experience green-roofs are all *muscinal* (or *Sedum*) green-roofs.
Secondly, the Kiosk green-roofs, presenting a more diversified range of vegetation structures, were studied to understand the effect of the variation of the *ground-level distance from the closest eco-hub [m]*, on the *spontaneous plant species diversity [H]* (**FIG. 3.1.1b**).
A higher diversity of spontaneous species was observed on the Kiosks closer to nature areas and parks (eco-hubs). Yet also this relationship is weak (LM: adjusted R-squared value of 0,07999).

3.2 Vegetation structure affects spontaneous plant species diversity

«Is the spontaneous plant species diversity on green-roofs influenced by the vegetation structure complexity of the planted vegetation on the green-roof?»

Vegetation structure, considering different definitions of it, affects spontaneous species diversity.
Firstly, vegetation structure in general (horizontal and vertical structure together), here defined as *vegetation structure complexity*, shows a significant positive relationship with spontaneous species diversity. Yet, the relationship is even stronger when the *green-roof age* is included in the influential variables, as shown in this GLM representation (**FIG. 3.2.1**). This means that older green-roofs with a more complex vegetation structure can welcome the highest spontaneous plant species diversity.

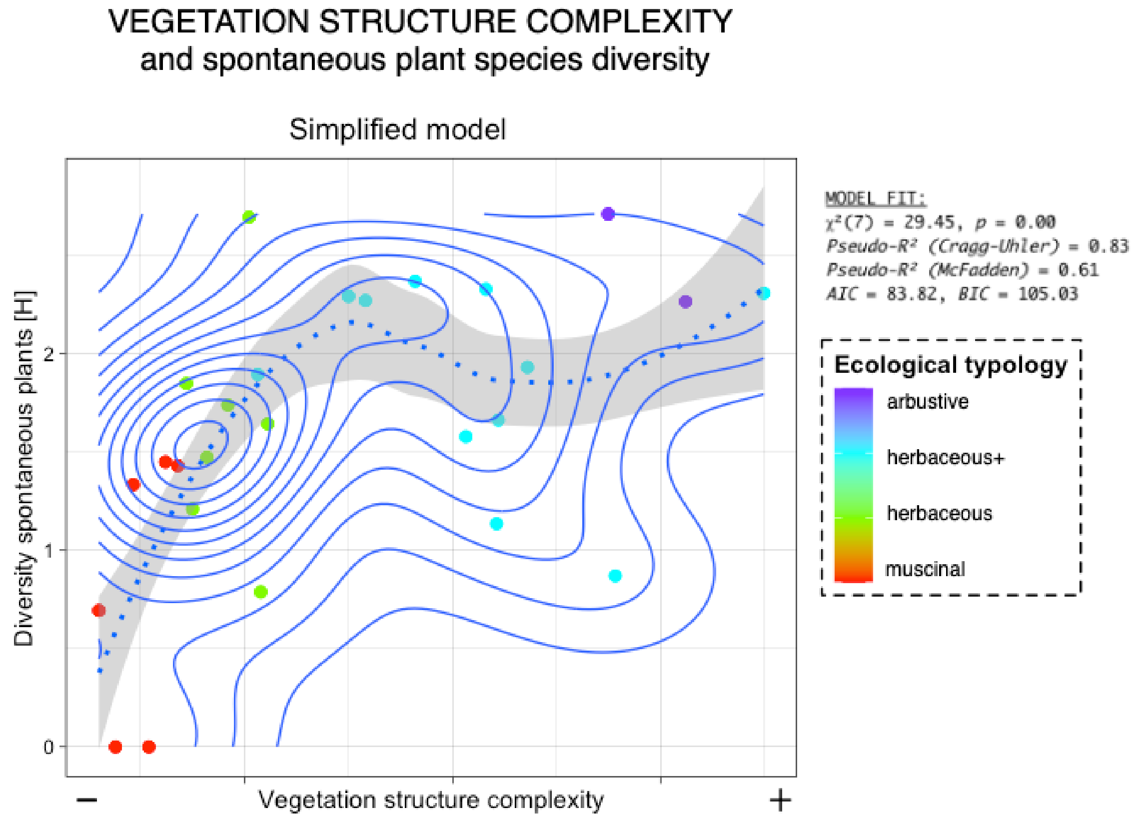


FIGURE 3.2.1. The relationship between vegetation structure complexity and spontaneous plants species diversity is summarised by this simplified GLM, which also considers the green-roof age. It includes a representation of the datapoints density (blue lines). The graph shows that the more the vegetation structure increases in complexity and the older is the green-roof, the higher spontaneous plant species diversity is. This GLM was previously selected amongst several others, including more or different variables than green-roof age, based on ANOVA tests, and convenience. The green-roofs (shown as datapoints) are distinguished based on their ecological typology.

The ecological concept highlighted by these research findings aligns with the habitat heterogeneity hypothesis by McArthur & McArthur (1961), yet adapting it to a different context, that is green-roofs. In fact, a higher structural complexity can contribute to create a

more differentiated range of micro-habitats or niches in terms of light and humidity conditions (Gao et al., 2014; Bergen et al., 2009). This can favour the establishment of a more diverse population of spontaneous plants. In this perspective, the higher amount of micro-habitat or niches can also be defined as a form of habitat heterogeneity.
The age of the green-roof can be relevant in the model because, based on observations and questions asked to the maintenance employees, the initially planted mix of species goes through several changes. On the one hand, there are species that tend to become dominant, often at expense of other species. On the other hand, recently installed green-roofs are easier to keep under control with maintenance than older green-roofs. So, the overall structure of the green-roof vegetation tends to become more complex over time. Therefore, older green-roof present a more intricated and heterogeneous structure of the vegetation, and this complexity favours the establishment of a more diversified range of spontaneous plant species.

Secondly, in the simplified model, as well as in several other data representations (**FIGG. 3.3.1.1, 3.3.1.2.a,b,c**), a pattern defined by the ecological typology of each green-roof is clearly visible. This conceptually interesting variable can be seen as a very simple and general indicator of the vegetation structure complexity. The ecological typology ‘herbaceous+’, representing green-roofs with a herbaceous cover higher than 50%, was added to highlight the difference with the ‘herbaceous’ green-roofs. Ecological typology shows a quite clear relationship with spontaneous plant species diversity, meaning that the more the vegetation shows a complex ecological typology, the more diverse the spontaneous vegetation is (**FIG. 3.2.2**).

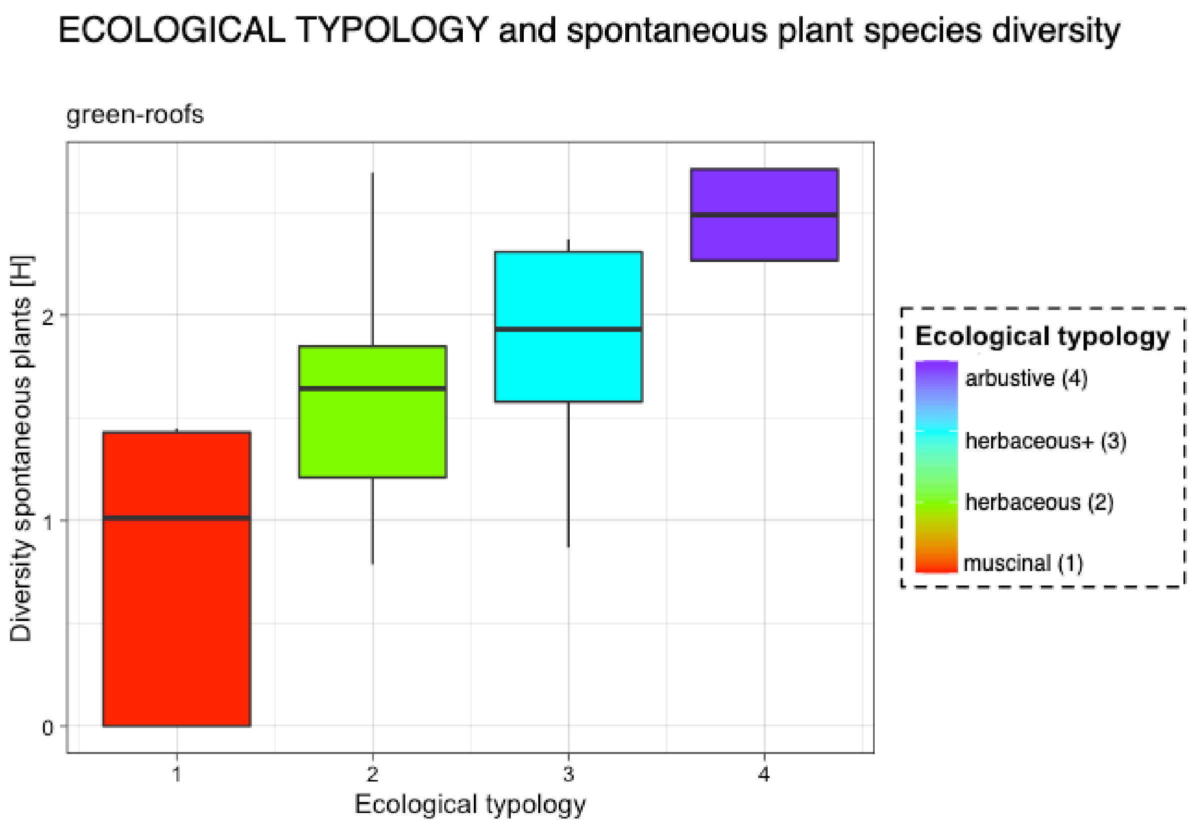


FIGURE 3.2.2. This boxplot shows that ecological typology is positively related to spontaneous plant species diversity. Thus, the more complex the ecological typology of each green-roof is, the higher

spontaneous species diversity was observed on the sampled green-roofs. The lowest values of spontaneous plant species diversity correspond to the simplest type of vegetation, that is muscinal green-roofs (1, red). Instead, the highest values of spontaneous plant species diversity correspond to the most complex vegetation found on the green-roofs, that is arbustive green-roofs (4, purple).

3.3 Other considerations

The effects of vertical vegetation structure, and horizontal vegetation structure on spontaneous plant species diversity are worth a mention, since these support the habitat heterogeneity hypothesis (McArthur & McArthur, 1961). Successively, it is interesting to report a few considerations about the recorded spontaneous plant species (86 out of 153).

3.3.1 More insights about vertical and horizontal structure

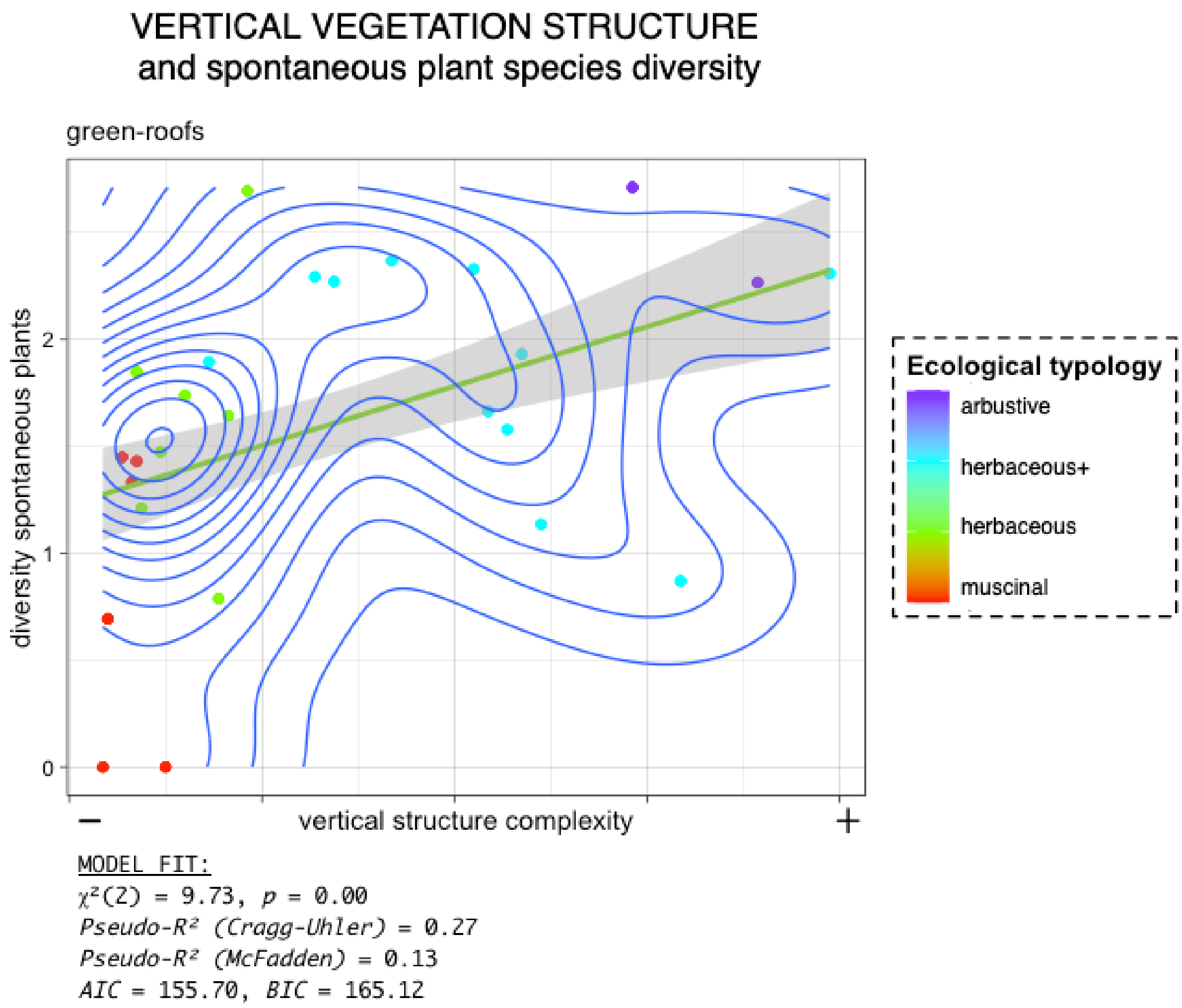


FIGURE 3.3.1.1. Visualisation of the positive relationship between vertical structure complexity and spontaneous plant species diversity. Also, there is a pattern in the ecological typology. This shows that the muscinal green-roofs (“musci”,red datapoints), presenting lower values of vertical structure complexity, also show a lower spontaneous species diversity than the herbaceous green-roofs (“herba”, “herba+”, blue and green datapoints), which have higher vertical structure complexity.

On the one hand, the *vertical vegetation structure* analysis (**FIG. 3.3.1.1**) shows that the higher the complexity of the vertical structure is, the higher spontaneous plant species diversity a green-roof will have. The ecological concept of vertical structure is included in the habitat heterogeneity hypothesis by McArthur & McArthur (1961), yet here is adapted to a green-roof context. This means that, a high vertical structure complexity of the green-roof vegetation, enhancing the habitat availability, can also favour the establishment of more diverse spontaneous plants.
On the other hand, in order to understand the ecological explanation of the *horizontal vegetation structure* trend, it is useful to observe the particular effect of muscinal, herbaceous, and arbustive cover on spontaneous plant species diversity.

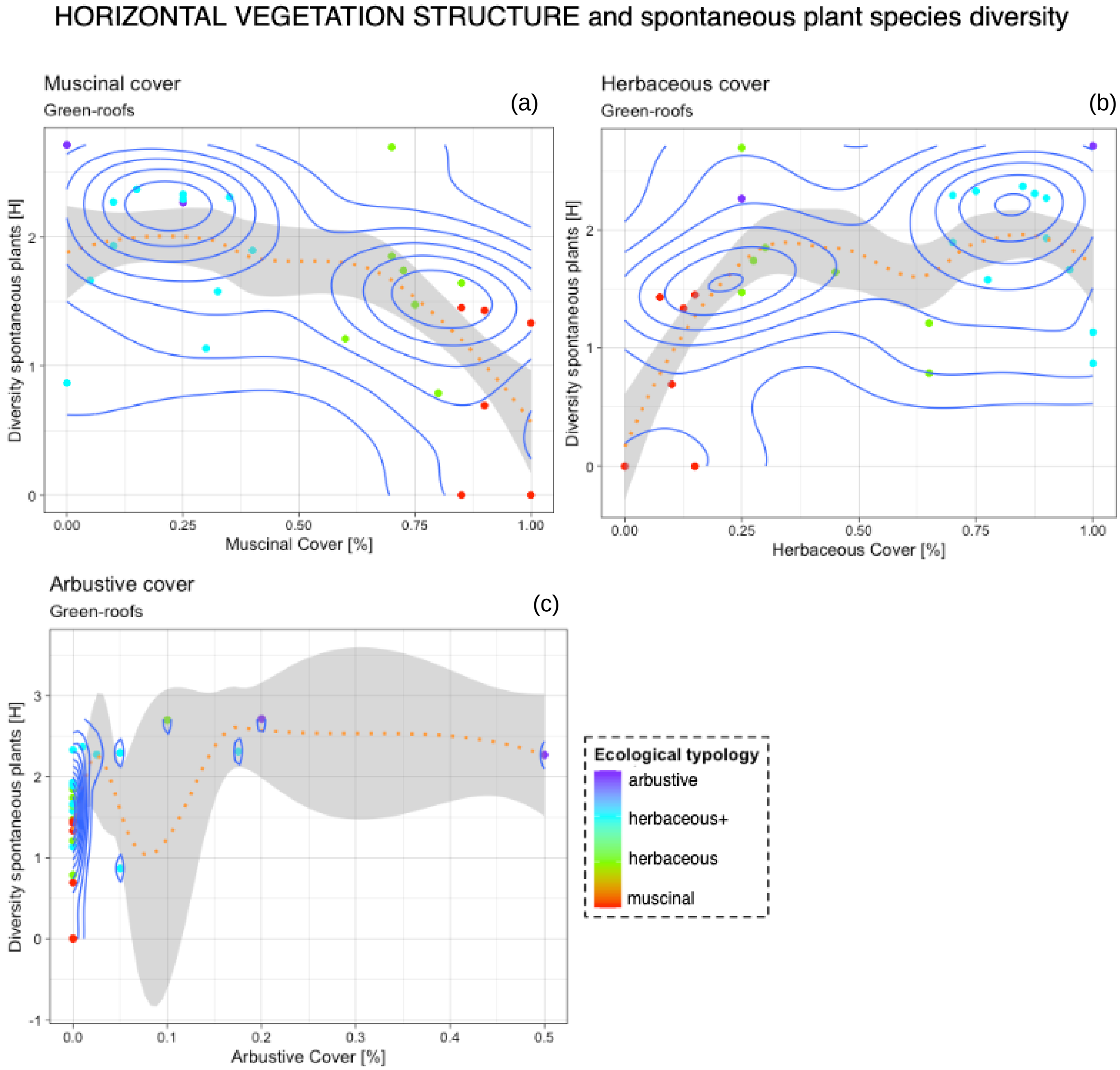


FIGURE 3.3.1.2. Visualisations of the effect of the muscinal cover percentage (a), herbaceous cover percentage (b), and arbustive cover percentage (c) on spontaneous plant species diversity, including a representation of the datapoints density (blue lines). The density lines are useful to understand the accuracy of the visual representation of the data, meaning that where there is a higher concentration of data-points, represented by accumulated density lines, the visualisation is more precise. (a) The trend shows that green-roofs with low values of muscinal cover present a higher spontaneous plant species diversity than the green-roofs with high muscinal cover, which are *Sedum*-dominated.

(b) The trend shows that green-roofs with low values of herbaceous cover present a lower spontaneous plant species diversity than the green-roofs with high muscinal cover, which are *Sedum*-dominated.
Additionally, a pattern is noticeable in the distribution of the green-roofs (a,b) sorted by ecological typology (colors of the data-points). The muscinal green-roofs (1, red) show the lowest values of spontaneous species diversity, thus the highest values of muscinal cover, while the arbustive (4, purple) and herbaceous+ (3, light-blue) green-roofs show the highest values of diversity, thus the lowest values of muscinal cover.
(c) The trend shows fluctuations and it does not appear particularly accurate. Where the density lines accumulate, the model is accurate and based on data-points, while where the density lines are loose, the model goes towards approximation. Taking this into account, the highest values of spontaneous plant species diversity correspond to about 20% of arbustive vegetation cover, yet the data-points are only a few and the graph displays an estimate of the trend.

Firstly, the *muscinal cover [%]* trend (**FIG. 3.3.1.2a**) starts decreasing significantly around 75%, and the lowest values of diversity correspond to the highest values of muscinal cover. The compactness of the muscinal cover might create a significant competition with spontaneous species in terms of light, soil, and other resources availability. In addition, sedum green-roofs are generally highly maintained in terms of weeding for aesthetical reasons. Yet, also muscinal green-roofs which are not maintained, show relatively low values of spontaneous species diversity. This might indicate poor environmental conditions of the green-roof, since certain Sedum species have low habitat requirements and they are highly adaptable (Butler & Orians, 2009). In fact, Sedum spp. can often become dominant in habitat conditions that are unfavourable to the establishment of other spontaneous plants with higher environmental requirements. The limiting factors can be low soil humidity and high light exposure, based on observations on the SmartRoof 2.0 and the VU green-roof.
Second, the *herbaceous cover [%]* trend (**FIG. 3.3.1.2b**) shows the most significant increase in spontaneous species diversity approximately between 0% and 25%. In this case, the lowest values of *herbaceous cover [%]* correspond to the lowest values of *spontaneous plant species diversity [H]*. A reason can be that, where the herbaceous cover is lower, is very likely that the muscinal cover is high and it can overcompete many spontaneous plant species. Herbaceous plants, in contrast, generally present a lower density than Sedum spp.
Third, the *arbustive cover [%]* trend (**FIG. 3.3.1.2c**), as noticeable from the datapoint density lines, is the least accurate of the three presented in this chapter, since the majority of the green-roofs analysed do not present arbustive vegetation. This makes clear that more data are needed to draw conclusions from this perspective. Yet, on the heterogeneous green-roofs, in the areas where arbustive plants are present, the spontaneous plant species diversity is higher (two case studies: SmartRoof 2.0 and VU Daktuin). This response can be associated with the variations in environmental conditions created by the bigger arbustive plants: these can provide shade, decrease evapotranspiration rates, and allow more sustainable use of the water (rainwater and irrigation).
So, at least from a theoretical point of view, the higher the arbustive cover is, the higher the spontaneous species diversity is. Yet, this needs further empirical verification (*3.4.1*).

3.3.2 Plant species diversity on the green-roofs of Amsterdam

The γ-diversity recorded on all the green-roofs analysed is 153 total species, of which 86 are spontaneous plants. The most common spontaneous plants are reported in **TABLE 3.3.2.1**.

What stands out here, is the high number of spontaneous species, taking into account the total number of species (56%). This point calls into question the unfavourable conditions of green-roof habitats, showing that a decent range of species can actually establish.
Furthermore, the fact that more than half of the species recorded were not planted (56%), highlights the possibility of improving the plant species selection for green-roofs, making it more efficient and accurate, for example including more native species. As evidence of this, the values of spontaneous species diversity would tend to decrease on green-roofs where the planted vegetation was consisting of native species, and these presented generally a good state of the vegetation (e.g. VU Daktuin).
Yet, different types of green-roofs were included in this research. In fact, relatively high spontaneous plant species diversity is observed on green-roofs presenting a more complex vegetation structure.
An interesting final note is that also a few arboreous species were recorded (e.g. *Ulmus minor, Crataegus monogyna*).

TABLE 3.3.2.1 *'The 10 most common spontaneous plants species on the green-roofs of Amsterdam'*.

1	Ceratodon purpureus (moss)
2	Poacea
3	Brachytecium rutabulum (moss)
4	Cerastium glomeratum
5	Erigeron canadensis
6	Trifolium dubium
7	Cerastium fontanum
8	Veronica arvensis
9	Epilobium ciliatum or montanum
10	Galium

4. Limitations of this research

Various limitations might have affected this thesis research, such as the data collection timeframe and the possible methodological constraints.
Firstly, the time range and setting of the data collection probably had an effect. On the one hand, it is important to remark that the first fieldwork day was on the 27th of May, and the last was the 7th of July. Within this 1,5 months timeframe, the vegetation changed. Even though the green-roofs were sampled in random order, this might have had an effect on the results. On the other hand, besides the practical constraints caused in a few of the fieldwork days, the unusual meteorological conditions might have affected the plant communities on the green-roofs.
Secondly, the green-roofs with simpler vegetation (e.g. Sedum roofs or simple herbaceous roofs) were more accessible to a thorough inventory, while the green-roofs with a more complex and intricated vegetation presented difficulties. The denser plots were at times difficult to see through properly without damaging the vegetation, and seedlings could be hidden.
In order to partially adjust the dataset in response to these issues, all the plants with a cover lower than 1-5% were not taken into account in most of the calculations. Plus, in the latest green-roof sampled, also dead plants were counted and identified when possible.

Finally, it is important to highlight what are the gaps in the datasets. For instance, most of the green-roofs analysed do not have an arbustive cover. Or also, a few of the green-roof characteristics of several green-roofs had to be estimated for data unavailability. Furthermore, several plants were impossible to identify, and for others was only possible to identify the genus. This perspective is taken into account in the following chapter, where a few recommendations for future research are given.

4.1 Recommendations for research

This research, with all the due limitations and constraints, opened a lot of interesting questions and research paths.
In order to continue along the lines of this research, the selection of a higher number of arbustive and arboreous green-roofs would be ideal. Since the green-roofs analysed in this research which presented arbustive vegetation showed interesting results in terms of biodiversity but were only three.

- *How does arbustive vegetation structure affect spontaneous plant species diversity?*

The green-roof age significance could be explored by studying the evolution over time of green-roof vegetation, to research green-roof successional mechanisms.

- *How do vegetation structure and spontaneous plant species diversity change over time?*

4.2 Recommendations for practitioners

Green-roof companies seem to be becoming more research-oriented. This is a positive change, since these companies have a crucial role in shaping the demand for green-roofs, and they can have a significant influence on general awareness. This research also aims to suggest a range of applicable strategies to green-roof companies, for projecting ameliorated green-roofs.

- Green-roofs with simple vegetation tend to welcome less spontaneous species, decreasing the necessity of weeding operations. Yet, this can be an indicator of poor habitat conditions of the green-roof environment. This means that, especially in the long term, further maintenance costs are difficult to avoid, for example replanting costs.
- Green-roofs with complex vegetation can welcome more spontaneous plants, meaning that the green-roof habitat conditions are good enough. However, this means that maintenance operations, especially weeding, require attention when the aesthetic requirements of the vegetation are strict. To respond to this, the planted species selection should include native plants, so these can occupy the ecological niches on the green-roof leaving little room for other undesired species. Additionally, native plants also present habitat requirements which can be satisfied without much supplementary care and maintenance, besides their commonly underrated aesthetical value. Additionally, heterogeneous green-roofs, with small shrubs, herbs, and Sedum, can enhance several ecosystem services associated with green-roofs (Lundholm et al., 2010).

5. Conclusions

To sum up, this research aimed to explore the habitat connectivity potential of green-roofs, in terms of habitat provision for spontaneous plant species. The effect of the distance from the ground-level habitat and vegetation structure complexity were investigated and targeted by the two research questions (a,b).

Firstly, spontaneous plant species diversity is not significantly influenced by the distance from the ground-level habitat, intended as the distance from the closest eco-hub included in the Nature Network of Amsterdam (Gemeente Amsterdam Klaas-Bindert de Haan, n.d.). Thus, contrarily than what was expected, the diversity of spontaneous plant species does not increase in the proximity of ground-level habitats. So, the effect of distance from ground-level habitat can be considered marginally. This allows focusing on a smaller scale, considering and examining the effect of local environmental variables, such as vegetation structure.

Secondly, spontaneous plant species diversity presents a positive relationship with vegetation structure complexity, intended as a combination of vertical and horizontal structure of the vegetation. This relationship is even stronger when the green-roof age is considered an influential parameter (**FIG. 3.2.1**). Or, this relationship can be simplified, conserving its validity, when the ecological typology is used as an indicator of vegetation structure complexity (**FIG. 3.2.2**). Yet, also vertical and horizontal structure show a positive relationship with spontaneous plants species diversity, hence supporting the habitat heterogeneity hypothesis (McArthur & McArthur, 1961) validity on green-roof vegetation. So, as predicted in the hypothesis, a higher complexity of the vegetation structure on green-roofs favours the establishment of a more diverse population of spontaneous plant species.

These research findings can contribute to build ecological knowledge about green-roofs, which is fundamental to achieve an optimal management strategy, and to take advantage of all the potential benefits of green-roofs. Also, in such perspective, this study opened many possibilities for future investigations.

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