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### ► **To cite this version:**

Carmen van Mechelen, Koenraad van Meerbeek, Thierry Dutoit, Martin Hermy. Functional diversity as a framework for novel ecosystem design: The example of extensive green roofs. *Landscape and Urban Planning*, 2015, 136, pp.165-173. <10.1016/j.landurbplan.2014.11.022>. <hal-01445201>

**HAL Id: hal-01445201**

**<https://hal.science/hal-01445201v1>**

Submitted on 12 Mar 2026

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# Functional diversity as a framework for novel ecosystem design: The example of extensive green roofs

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## A B S T R A C T

Novel urban ecosystems have recently gained importance and a consensus grows that ecosystem services are linked to ecosystem properties that in turn can be predicted by functional diversity (FD) of plant communities. Ensuring quality of life in cities is essential and approaches to improve ecosystem services should be encouraged. Here we analyzed the initial plant composition of commercial extensive green roof systems in terms of FD and propose two methods to compose species lists that maximize FD. Clustering techniques grouped the systems in three green roof types that differ in species richness and composition, substrate depth and installation method. Differences in FD and species richness between the types were considerable and correlations between FD and species richness were strongly positive, suggesting that species-rich systems generally have higher FD and thus offer better ecosystem services. Green roof systems that comprise only succulents have significant lower FD values compared to systems containing more diverse vegetation. Within the green roof types there was room for improvement of FD. Based on a species trait dissimilarity matrix, species lists that maximize FD for every green roof type were created. FD analysis of novel ecosystems enables the design of both species-poor and species-rich green roof systems with improved overall ecosystem services value. The described approach is generic in nature and can be used for a broad range of novel ecosystems and urban green elements. We believe that designing functional diverse plant systems will support a more sustainable urban planning and improve the quality of urban life.

### Keywords:

Ecosystem services  
Functional diversity  
Green roofs  
Novel ecosystems  
Plant traits  
Species richness

## 1. Introduction

Biodiversity is believed to be the major driver of ecosystem services through ecosystem processes and functions (Cardinale et al.,

2012; Gamfeldt et al., 2013; Pinto, de Jonge, & Marques, 2014; Quijas et al., 2012; Tzoulas et al., 2007). Overall there is a positive relation between ecosystem properties (e.g. resilience, resistance) and biodiversity and there is increasing evidence that biodiversity improves the stability of ecosystems through time (for a review, see Cardinale et al., 2012). There is also sufficient evidence that biodiversity either directly influences or is strongly correlated with provisioning and regulating services (cf. Cardinale et al., 2012; Isbell et al., 2011). Furthermore, consensus is growing that functional traits, and especially the range and value of those traits, rather than species richness and evenness are important for the

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provisioning of ecosystem services (e.g. Hooper et al., 2005; Lavorel et al., 2011). Functional trait composition and diversity can be compared amongst plant communities through a series of functional diversity (FD) indices (Mouchet, Villegger, Mason, & Mouillot, 2010; Petchey, Hector, & Gaston, 2004).

Recently, as a result of advancing habitat loss, land use changes and urbanization, the concept of novel ecosystems has gained momentum. These are, by definition, self-organizing systems originating from human interference and with actual altered biotic, abiotic and social components as compared to the prevailing historical ecosystems (Hobbs, Higgs, & Hall, 2013). Urban ecosystems, like green roofs, parks and gardens, fall within this definition due to their novel elements but differ from novel ecosystems in cultivated or degraded landscapes because continued management is necessary (Hobbs et al., 2006; Kowarik, 2011; Lundholm & Richardson, 2010; Perring et al., 2013).

Based on evidence of previous studies, we assume that designing functional diverse urban ecosystems will improve ecosystem services (cf. Isbell et al., 2011; Pinto et al., 2014; Witthinghill, Rowe, Schutzki, & Cregg, 2014) and the life quality of urban residents (Chiesura, 2004; Tzoulas et al., 2007; Wolch, Byrne, & Newell, 2014). In this study the FD of novel ecosystems is analyzed and two generic methods for improved design of novel ecosystems in terms of species composition are proposed. The methodology is inspired by the Noah's Ark Problem (cf. Billionnet, 2013), because the goal is to achieve optimal allocation of a limited amount of resources by maximizing the FD. We use extensive green roofs, which offer many benefits in urban areas such as stormwater management and mitigation of the urban heat island effect (Carter & Jackson, 2007; Gaston, Avila-Jiménez, & Edmondson, 2013; Oberndorfer et al., 2007; Tzoulas et al., 2007), as a case study to explore and illustrate the methods. Extensive green roofs are semi-artificial ecosystems with vegetation on substrate (generally 2–15 cm in depth) and specialized materials placed on a building's roof (Oberndorfer et al., 2007). Species selection in these novel urban ecosystems is often determined by criteria such as commercial availability, aesthetic qualities, adaptation to the environmental conditions and substrate depth (Getter & Rowe, 2006). A practical approach that directs to plant species with improved ecosystem services value is a meaningful addition to this criteria list, and because the approach is generic in nature, the methods will be useful for the design of other novel ecosystems as well.

The specific goals of this study were to:

- (i) Analyze the initial plant species composition, as provided by commercial extensive green roof systems, in terms of FD.
- (ii) Offer a methodology to optimize species choice for incorporation into extensive green roof design, making use of the FD approach.

## 2. Methodology

### 2.1. System and trait selection

The European Federation of Green Roof Associations was used to select extensive green roof systems ([www.efb-greenroof.eu](http://www.efb-greenroof.eu), consulted on 24/02/2013). The webpages of all the companies associated with this Federation were screened for extensive green roof systems and their corresponding plant species (i.e. species that are proposed by the green roof companies). When information was not published online, we requested the species lists from the company. In total, 57 systems originating from 19 green roof companies spread over six European countries were used in the analysis (Supporting information 1A). Some companies are active in multiple countries, so the systems provided by them are assumed useful

for Northern, Western and Central Europe. All systems together accounted for 199 vascular plant species (Supporting information 1B); nomenclature follows [The Plant List \(2013\)](#). Varieties and subspecies were not taken into account. In order to link essential variation in green roof systems with FD, we collected and partly derived information on percentage of succulent species, substrate depth, installation method (cuttings, mat, seeds or plugs) and species richness.

Trait selection (29 in total; [Table 1](#)) was determined by important green roof ecosystem properties as explicitly mentioned in specific literature on green roofs: [Cook-Patton and Bauerle \(2012\)](#), [Dakin, Benjamin, and Pantiel \(2013\)](#), [Getter and Rowe \(2006\)](#), [Lundholm, MacIvor, MacDougall, and Ranalli \(2010\)](#), [Oberndorfer et al. \(2007\)](#), [Oudolf and Kingsbury \(2013\)](#), [Robinson and Lundholm \(2012\)](#) and [Wolf and Lundholm \(2008\)](#). Trait values for the plant species were obtained from multiple sources ([Table 1](#)).

### 2.2. Data analysis

#### 2.2.1. Exploring the green roof systems

The 57 green roof systems were clustered based on their plant species composition using hierarchical clustering with Sørensen distance measure and flexible beta ( $\beta = -0.25$ ) as group linkage method ([McCune & Mefford, 1999](#)). We used Indicator Species Analysis ([Dufrene & Legendre, 1997](#)) to obtain the optimal number of system types in the cluster analysis and to define species that significantly differentiate these types. Clustering and Indicator Species Analysis were performed in PCord 6.0 (MjM Software, USA). Non-parametric tests (Kruskal–Wallis and Pearson  $\chi^2$ ) were used to explore significant differences between the system types in terms of system characteristics. Statistical tests were performed with IBM SPSS Statistics 22.0 (SPSS Inc., Chicago, IL).

#### 2.2.2. Diversity analysis

FD was quantified by two independent diversity indices ([Mason, Mouillot, Lee, & Wilson, 2005](#)). The richness index is the amount of trait space filled by the community and the evenness index is a measure of the uniformity of distribution of species in trait space. Functional richness was quantified in this study with FD<sub>pg</sub> (referring to the FD measure as proposed by [Petchey & Gaston, 2002](#)). FD<sub>pg</sub> is the total branch length of the functional dendrogram constructed using a dissimilarity matrix (Gower distance) based on the species functional traits. Functional evenness was quantified with FE<sub>ve</sub> as proposed by [Villégger, Mason, and Mouillot \(2008\)](#). The FD indices were calculated using the FD ([Laliberté & Shipley, 2013](#)), Ape ([Paradis et al., 2013](#)) and Picante package ([Kembel et al., 2010](#)) in R2.15.3 ([R Core Team, 2013](#)). FD<sub>pg</sub> and FE<sub>ve</sub> were calculated for every green roof system and related to species richness using Spearman rank correlation ( $r_s$ ). Differences in diversity indices between the system types were tested using Kruskal–Wallis tests at a significance level of 0.05.

#### 2.2.3. Species selection for optimization of green roof ecosystem functioning

Each species has its own habitat requirements and not all species can be applied on every green roof type. In order to optimize ecosystem services of green roof systems, we compiled a species list per green roof type in which FD is maximized (FD<sub>Max1</sub>). Richness and evenness are both important factors that influence ecosystem properties, but as the calculation of FE<sub>ve</sub> is very complex, we chose to maximize FD<sub>pg</sub>. We started with a species list and accompanying functional trait matrix per green roof type with the species that were present in the systems of that type. A separate species dissimilarity matrix for each of the green roof types was calculated with the Gower index as distance measure (in R2.15.3). The selection process started with the two species with the highest dissimilarity

**Table 1**

List of 29 traits used for the FD approach, selected after screening of the literature on ecosystem services of green roofs. Every trait is supplemented with the following information: ecosystem properties explaining the importance of the trait for the ecosystem service; ecosystem service category (C: cultural; R: regulating; S: supporting; P: provisioning); brief description, variable type (N: nominal; S: scale; O: ordinal) and missing values which indicate the % of species for which no trait information could be found.

Plant trait	Ecosystem properties	Ecosystem service category	Brief description	Variable type	% missing values
Design type	Structural complexity (SC)	C, S	Ranking order of planting. 1. base plants; 2. matrix plants; 3. scatter plants	N	0
Drought tolerance	Drought tolerance (DT)	C	0. none, very low; 1. medium; 2. high	O	0
Flower colour	Aesthetic (A); attract pollinators (Pol); habitat (H)	C, S	1. yellow, red, orange; 2. white; 3. blue, violet, purple, pink; 4. brownish; 5. green, discreet	N	0
Flowering time	A; Pol	C, S	Season when flowering starts. 1. spring; 2. early summer; 3. mid summer; 4. late summer/autumn; 5. winter	N	1
Lateral spread	SC	C	0. none; 1. moderate; 2. extensive	O	2
Leaf area	Evapotranspiration (ET)	R	mean leaf size (mm <sup>2</sup> )	S	31
Leaf colour	A	C	1. green (including dark- and light green); 2. blue-green; 3. grey-green	N	0
Leaf dry mass	Biomass (BM)	S, R	whole leaf dry mass (mg)	S	55
Leaf phenology	ET; SC; A	C, S, R	Timing of leaf expansion. 1. spring green; 2. summer green; 3. overwintering green; 4. persistent green	N	4
Leaf type	SC	C	1. simple; 2. compound	B	21
Persistency	Self-sustainability (SS)	C	Capacity of the plant to remain at the same place for multiple years. 1. low; 2. medium; 3. high	O	2
Photosynthetic pathway	ET; DT	C, R	1. C3; 2. CAM	B	17
Plant architecture	ET; SC	C, S, R	Relationship between stem and leaf. 1. basal leaves; 2. stem leaves; 3. multiple stem; 4. branched; 5. grasses	N	0
Plant height	BM; SC	C, S, R	Mean individual height (m)	S	2
Plant life form	ET; BM; SC	C, S, R	Life form categories according to Raunkiaer. 1. phanerophyte; 2. chamaephyte; 3. hemicryptophyte; 4. geophyte; 5. therophyte	N	0
Plant longevity	BM; SC; SS	C, S, R	Longevity of the plant. 1. annual; 2. biennial; 3. short living perennial, <10 years; 4. real perennial, >10 years	O	1
Plant strategy type	DT	C	Survival strategies according to CSR-model of Grime. 1 = c (competitor); 2 = s (stress tolerant); 3 = r (ruderal); 4 = cs; 5 = cr; 6 = sr; 7 = crs	N	20
Pollinator reward	Pol; H	S	0. none; 1. nectar; 2. pollen; 3. nectar + pollen	N	24
Provisioning value	Provisioning	P	Direct value for humans. 0. none; 1. medicine; 2. herb; 3. edible plant parts	N	0
Relative growth rate	BM	R	1. slow; 2. medium; 3. fast	O	71
Rooting depth	ET; SC; DT	R	Average depth of the roots (m)	S	71
Seed bank index	SS	C	Proportion of short and long term persistent seed records on total number of records per species	S	39
Self-seeding	SS	C	Capacity of the plant to multiply itself through seeds. 1. low; 2. medium; 3. high	O	1
Shoot growth form	SC	C, S, R	Orientation of stem: 1. erect; 2. ascending to prostrate; 3. prostrate	N	25
Structural design interest	A	C	Duration of the plant's design interest. 1. short, <3 months; 2. medium, 3–9 months, flowers and seed heads; 3. long, ≥9 months, good seed heads	O	1
Succulence	ET; DT	C, R	Capacity of the plant to store water in the leaves. 0. none; 1. yes	B	0
Ultraviolet feature	Pol; H	S	UV-visibility of the flower. 0: no; 1: yes	B	34
Vegetative dispersion	SS	C	Capacity to disperse through vegetative growth. 0. none; 1. low; 2. medium; 3. high	O	0
Woodiness	BM; DT; SC	C, S, R	0. non woody; 1. semi-woody; 2. woody	O	0

Source references: [Cornelissen \(1996\)](#), [Couplan \(2009\)](#), [Fitter and Peat \(1994\)](#), [Kleyer et al. \(2008\)](#), [Kühn, Durka and Klotz \(2004\)](#), [Oudolf and Kingsbury \(2013\)](#), and [Shipley \(1995\)](#).

value. Next, a new species was added that maximized the average dissimilarity to the species that were already in the list. This step was repeated until the average species richness of that green roof type was reached. The final result was a species list per green roof type with the number of species equal to the average species richness of that green roof type that maximized FDpg. In order to calculate the gain in FDpg of the optimized species lists, we wanted to compare the FDpg of the optimized species lists with the FDpg values of the initial green roof systems. However, values of FDpg

depend on the number of species in the functional dendrogram and FDpg values that are calculated from different dendrograms can therefore not be compared. In order to be able to compare the FDpg of the optimized species lists with the FDpg values of the initial green roof system, we also calculated the FDpg of the optimized species lists based on the functional dendrogram constructed with all species.

Because not all species in the optimized species lists are readily available in every commercial assortment, the optimized species

**Table 2**  
Summary of the three green roof types in terms of key variables. Significance of differences between the types was tested using: (A) Kruskal–Wallis tests for quantitative variables. Average values and standard deviation are listed for every type, followed by a letter indicating the significant differences (Kruskal–Wallis post hoc test). (B) Pearson Chi<sup>2</sup> tests for nominal variables, with indication of number of green roof systems per category for every type (\*\*\*)  $p \leq 0.001$ .

(a) Quantitative variables	Kruskal–Wallis (significance)	<i>Sedum</i> type	<i>Dianthus-Thymus</i> type	<i>Linaria-Galium</i> type
# Green roof systems		22	27	8
Species richness	33.10 (***)	8.18 ± 2.3a	22.33 ± 8.4b	19.50 ± 7.8b
Substrate depth	34.50 (***)	4.91 ± 1.5a	9.22 ± 2.6b	9.63 ± 2.3b
Percentage of succulent species	42.96 (***)	97.73 ± 9.2b	18.87 ± 16.3a	6.88 ± 9.7a
(b) Nominal variables	Pearson Chi <sup>2</sup> (significance)	<i>Sedum</i> type	<i>Dianthus-Thymus</i> type	<i>Linaria-Galium</i> type
Installation method	54.50 (***)			
Cuttings		9	0	0
Mat		12	2	1
Seeds		0	18	1
Plugs		1	7	6

lists are not very practical. Therefore, we also provided a method to optimize FD of green roofs that is practically applicable by green roof companies (FDMax2). Per green roof type the species present in the green roof type were classified in functionally similar groups based on the functional dendrogram. The number of groups corresponded again to the average species richness of the green roof type. By choosing one species of each group, the maximum FDpg is approached.

The proposed methods FDMax1 and FDMax2 offer a solution to the Noah's Ark Problem (Billionnet, 2013), in which FD of the green roof types is maximized. Billionnet (2013) also addressed this problem by using nonlinear mixed-integer programming, a complex and elaborate method because transformations and logarithmic function techniques are necessary to account for the nonlinearity. Here we tackled the problem in a more simple way by using a dissimilarity matrix (FDMax1) and hierarchical clustering techniques (FDMax2).

### 3. Results

#### 3.1. Green roof type description

Clustering the 57 extensive green roof systems resulted into three types, each characterized by a number of significant indicator species (Supporting information 1B) and attributes (Table 2). The 22 green roof systems belonging to type 1, hereafter called 'Sedum type', contained mainly succulent species, had the shallowest substrate depth (5 cm on average) and species were mainly installed by cuttings or mats. Species richness was significantly lower than those of type 2 and 3 ( $8.2 \pm 2.32$ , Table 2) and eight *Sedum spp.* were significantly associated with this type. Type 2, or 'Dianthus-Thymus type' (after two highly significantly associated species, see Supporting information 1B), contained 27 systems with more diversified vegetation, although *Sedum spp.* were still present in most systems. The vegetation was mainly installed by seeding on a substrate of around 9 cm thick. The species richness was high ( $22.3 \pm 8.43$ ), with 17 species that were significantly associated with this type. The eight systems belonging to type 3, the 'Linaria-Galium type', contained 30 indicator species and were characterized by the almost absence of succulent species. Installation of plants was mainly achieved by application of plugs. Substrate depth and species richness were not significantly different from the *Dianthus-Thymus* type.

#### 3.2. Diversity analysis

Kruskal–Wallis test results showed significant differences between the three green roof types for the functional diversity measures (Fig. 1). The largest differences were observed for FDpg

( $p$ -values  $< 0.001$ ), where values of the *Sedum* type were significantly lower compared to the *Dianthus-Thymus* and *Linaria-Galium* type. Differences between green roof types were also significant for FEve ( $p$ -value  $< 0.05$ ), with the *Sedum* type showing significant higher values than the *Dianthus-Thymus* type. Despite the significant differences, values for FEve ranged from 0.96 to 1, suggesting a rather uniform distribution of species in trait space. The boxplots also showed considerable variation in the value range of FDpg for the *Dianthus-Thymus* and the *Linaria-Galium* type.

FDpg was strongly positively correlated with species richness ( $r_s = 0.96$ ;  $p$ -values  $< 0.001$ ) (Fig. 2). So the higher the number of species in the green roof system, the higher the FD and the supposed positive impact on ecosystem services. Between FEve and species richness, no correlation was found. Although systems from the *Sedum* type were situated at low species richness, the systems of the *Dianthus-Thymus* and *Linaria-Galium* types showed variation on the X-axis, meaning that the observed variation in Fig. 1 can be explained by the systems variety in species richness. For a given species richness, the values of FDpg showed some variation on the Y-axis, indicating that a better design in terms of species selection is possible.

#### 3.3. Maximizing functional diversity

Table 3 shows the combined results of FDMax1 and FDMax2. A complete table with the results of FDMax2 is included in Supporting information 1C. Species with the highest functional dissimilarity were for the *Sedum* type *Phedimus selskianus* and *Prunella grandiflora*, for the *Dianthus-Thymus* type *Sedum montanum* and *Tripleurospermum maritimum* and for the *Linaria-Galium* type *Papaver rhoeas* and *Sedum album* (Table 3a). *P. selskianus* could for example be replaced by *S. album*, which belongs to the same group according to FDMax2 (Table 3b). In the same way, *T. maritimum* could be replaced by *Calendula arvensis* or *Arenaria serpyllifolia*. These species substitutions illustrate the practical aspects of FDMax2. For all the green roof types, the attained value of FDpg by using FDMax1 was higher than the initial FDpg value of the green roof type. For a *Sedum* type system containing eight species FDpg increased with 22%, for a *Dianthus-Thymus* type system containing 22 species FDpg improved 10% and for a *Linaria-Galium* type system with 20 species FDpg increased with 7%.

### 4. Discussion

#### 4.1. The functional diversity approach and extensive green roof systems

The objective of this study was to examine extensive green roof systems, exemplary for novel urban ecosystems, and to offer an

**Table 3**  
 Combined results of the FD maximization methods FDMax1 and FDMax2, offering an exact and practical species list respectively. Number of groups corresponds to the average species richness of every type. Species of FDMax1 are underlined and the superscript numbers rank these species according to decreasing functional dissimilarity. The other species (up to 6, for the complete list we refer to Supporting information 1C) can be used as alternatives. For comparison, both the system FD and the maximized FD of FDMax1 for a system with the average species richness are shown.

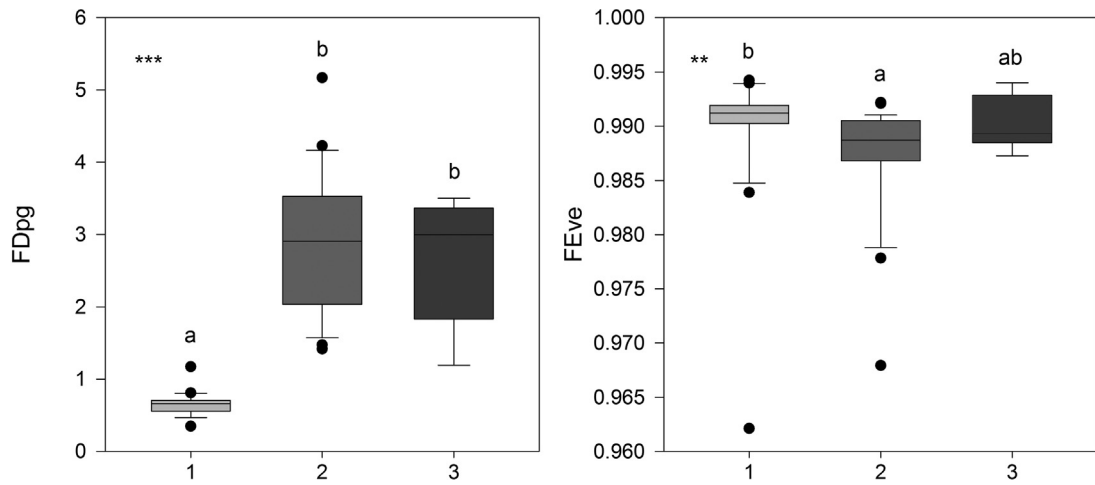
System type	Sedum type		Dianthus-Thymus type		Linaria-Galium type	
Average species richness	8		22		20	
System FDpg	0.9		2.9		2.8	
Maximized FDpg	1.1		3.2		3.3	
Group						
1	<u>Phedimus selskianus</u> <sup>1</sup> <u>Sedum album</u> <u>Sedum hybridum</u>	<u>Sedum lydium</u> <u>Sedum rupestre</u> <u>Sedum sexangulare</u> . . .	<u>Achillea millefolium</u> <u>Anthemis tinctoria</u> <u>Daucus carotus</u>	<u>Leucanthemum vulgare</u> <u>Pimpinella saxifraga</u> <u>Trifolium arvense</u>	<u>Achillea millefolium</u> <u>Daucus carota</u> <u>Echium vulgare</u>	<u>Leucanthemum vulgare</u> <u>Reseda lutea</u>
2	<u>Campanula portenschlagiana</u> <sup>6</sup>	<u>Campanula poscharskyana</u>	<u>Aurinia saxatilis</u> <sup>11</sup>	<u>Achillea tomentosa</u>	<u>Agrimonia eupatoria</u> <sup>17</sup>	<u>Hypericum perforatum</u>
3	<u>Sedum spathulifolium</u> <sup>8</sup>		<u>Dianthus carthusianorum</u> <u>Dianthus deltooides</u> <u>Linum perenne</u>	<u>Potentilla argentea</u> <u>Potentilla verna</u> <u>Prunella grandiflora</u> . . .	<u>Saxifraga granulata</u> <sup>16</sup> <u>Armeria maritima</u> <u>Bellis perennis</u>	<u>Geranium sanguineum</u> <u>Leontodon hispidus</u> <u>Primula veris</u> . . .
4	<u>Hylotelephium spectabile</u>		<u>Allium roseum</u> <sup>14</sup> <u>Iris pumila</u> <sup>4</sup> <u>Allium schoenoprasum</u>	<u>Allium sphaerocephalon</u> <u>Iris tectorum</u> <u>Leopolda comosa</u>	<u>Anthemis tinctoria</u>	
5	<u>Prunella grandiflora</u> <sup>2</sup>		<u>Anemone pulsatilla</u>		<u>Anthyllis vulneraria</u>	<u>Lotus corniculatus</u>
6	<u>Saxifraga cotyledon</u> <sup>3</sup>	<u>Sedum hispanicum</u>	<u>Armeria maritima</u> <u>Briza media</u> <u>Dianthus anatolicus</u>	<u>Primula veris</u> <u>Saxifraga granulata</u> <u>Saxifraga paniculata</u> . . .	<u>Carex flacca</u> <sup>3</sup>	
7	<u>Sedum cauticola</u> <sup>4</sup> <u>Sedum cyaneum</u> <sup>7</sup>	<u>Sedum ewersii</u> <u>Sedum telephium</u>	<u>Anthoxanthum odoratum</u> <u>Carex sylvatica</u> <u>Euphorbia cyparissias</u>	<u>Festuca glauca</u> <u>Festuca ovina</u> <u>Koeleria glauca</u> . . .	<u>Centaurea cyaneus</u> <sup>6</sup>	<u>Papaver rhoeas</u> <sup>1</sup>
8	<u>Sempervivum tectorum</u> <sup>5</sup> <u>Sempervivum arachnoideum</u>	<u>Sempervivum globiferum</u> <u>Sempervivum montanum</u>	<u>Anthyllis vulneraria</u> <u>Lotus corniculatus</u>	<u>Petrorhagia saxifraga</u>	<u>Cichorium intybus</u> <sup>15</sup> <u>Knautia arvensis</u> <sup>4</sup> <u>Pseudolysimachion spicatum</u> <sup>18</sup>	<u>Linaria vulgaris</u> <u>Scabiosa columbaria</u> <u>Silene vulgaris</u> . . .
9			<u>Aquilegia vulgaris</u>		<u>Centaureum erythraea</u> <sup>14</sup>	<u>Viola tricolor</u> <sup>10</sup>
10			<u>Papaver rhoeas</u> <sup>7</sup> <u>Tripleurospermum maritimum</u> <sup>2</sup> <u>Arenaria serpyllifolia</u> <u>Bromus tectorum</u> <sup>5</sup>	<u>Calendula arvensis</u> <u>Viola arvensis</u>	<u>Dianthus arenarius</u> <u>Plantago media</u>	<u>Silene uniflora</u>
11					<u>Thymus serpyllum</u> <sup>19</sup> <u>Dianthus deltooides</u> <u>Glechoma hederacea</u>	<u>Jasione montana</u> <u>Thymus praecox</u> <u>Veronica officinalis</u>
12			<u>Erodium cicutarium</u> <sup>12</sup>	<u>Centaurea cyanus</u> <sup>19</sup>	<u>Festuca ovina</u> <sup>12</sup> <u>Festuca rubra</u>	<u>Pilosella officinarum</u>
13			<u>Cerastium arvense</u> <u>Cerastium tomentosum</u>	<u>Sagina subulata</u>	<u>Filipendula vulgaris</u> <sup>7</sup>	
14			<u>Teucrium chamaedrys</u> <sup>17</sup> <u>Clinopodium alpinum</u> <u>Helianthemum nummularium</u>	<u>Thymus pulegioides</u> <u>Thymus serpyllum</u> <u>Thymus vulgaris</u> . . .	<u>Geum rivale</u> <sup>13</sup> <u>Galium verum</u> <u>Potentilla neumanniana</u>	<u>Potentilla reptans</u> <u>Ranunculus acris</u>
15			<u>Clinopodium vulgare</u>		<u>Helianthemum nummularium</u> <sup>5</sup>	
16			<u>Draba aizoides</u> <u>Hieracium aurantiacum</u> <u>Hieracium pilosella</u>	<u>Pilosella rubra</u> <u>Silene otites</u>	<u>Plantago coronopus</u> <sup>9</sup>	

Table 3 (Continued)

System type	Sedum type	Dianthus-Thymus type	Linaria-Galium type
17	<i>Echium vulgare</i> <i>Iberis sempervirens</i>	<i>Satureja subspicata</i>	<i>Ranunculus bulbosus</i> <sup>1</sup>
18	<i>Euphorbia myrsinites</i> <sup>13</sup> <i>Sedum album</i> <sup>15</sup> <i>Sedum caucicolae</i> <sup>6</sup> <i>Sedum montanum</i> <sup>1</sup>	<i>Sedum stenopetalum</i> <sup>20</sup> <i>Sempervivum arachnoideum</i> <sup>8</sup> <i>Sempervivum tectorum</i> <sup>22</sup> ...	<i>Rhinanthus minor</i> <sup>20</sup>
19	<i>Verbasum nigrum</i> <sup>9</sup> <i>Verbasum phlomoidees</i> <sup>16</sup> <i>Verbasum lychnitis</i> <sup>21</sup>	<i>Malva moschata</i> <i>Inula conyza</i> <i>Verbasum phoeniceum</i> ...	<i>Sanguisorba minor</i>
20	<i>Lavandula angustifolia</i> <sup>3</sup>		<i>Sedum album</i> <sup>2</sup>
21	<i>Ranunculus bulbosus</i> <sup>10</sup>		<i>Sedum acre</i> <sup>8</sup>
22	<i>Sanguisorba minor</i> <sup>18</sup>		

applicable approach to achieve better ecosystem services. The role of green roofs in offering a variety of ecosystem services becomes increasingly acknowledged in scientific literature (e.g. Carter & Jackson, 2007; Cook-Patton & Bauerle, 2012; Gaston et al., 2013; Lundholm et al., 2010; Oberndorfer et al., 2007; Perring et al., 2013). The specific ecosystem properties on which the trait selection was based (Table 1) are essential to provide those services. Plant evapotranspiration and biomass are properties influencing the regulating services climate regulation and water management. Traits like flower color, flowering time and pollinator reward help to attract pollinators or provide habitat for local flora and fauna, hence contributing to the supporting ecosystem services. The provisioning component of ecosystem services is determined by the trait provisioning value, which indicates if a species is of potential value for humans in terms of medicinal use or edibility. The cultural service is determined by the green roof's esthetic and amenity value (Dakin et al., 2013). Drought tolerance and self-sustainability are properties necessary to cope with extreme conditions typical for green roof environments, and hence ensure the resilience of the system. This is essential for the amenity value, and thus the cultural service, of the green roof (Getter & Rowe, 2006; Oberndorfer et al., 2007). Finally, structural diversity, determined by variation in multiple plant traits such as height, architecture and longevity, is an important esthetic determinant, but contributes also highly to the other services (Cook-Patton & Bauerle, 2012; Oudolf & Kingsbury, 2013). Table 1 clearly indicates that the selected plant traits relate to different and often multiple ecosystem services. Therefore, we assumed that the ecosystem services are adequately represented by the selected traits.

Similar to Madre, Vergnes, Machon, and Clergeau (2014), who proposed an ecological oriented green roof typology, the extensive green roof systems could be classified both on technical system properties (Table 2) and diversity values (Fig. 1). Succulent species, characteristic for the systems in the *Sedum* type, are the most commonly applied species on extensive green roofs. Their specific photosynthesis pathway (crassulacean acid metabolism) makes them better suited to withstand extreme conditions on roofs (Oberndorfer et al., 2007), and they have the greatest potential in terms of applicability on existing roofs, as they are easy to install and relatively light weight due to shallow substrate depth requirements. However, the FD of *Sedum* systems was significant lower compared to the other two green roof types, but we showed that FD could be improved with 22% by using FDMax1. These species-poor systems can thus become ecologically more interesting by considering alternative species. Although the FD analysis demonstrated that species-rich systems (the *Dianthus-Thymus* and the *Linaria-Galium* type) have higher FD values and hence potentially provide 'better' ecosystem properties (cf. Gamfeldt et al., 2013), we showed that even in these systems the FD could be increased up to 10%. The higher biomass and leaf area index of plants in these green roof types result in a higher evaporative capacity which improves stormwater management and temperature regulation (Lundholm et al., 2010). The structural diversity of these systems also supports the cultural, supporting and regulating ecosystem services (Cook-Patton & Bauerle, 2012). However, more diverse systems do impose constraints like a higher weight and cost, and more complexity and maintenance (cf. Snodgrass & McIntyre, 2010). As less succulent species are present in the species-rich green roof systems, the ability of these systems to tolerate drought could be questioned. In a green roof context, drought tolerance is often equated to only succulence. However, drought tolerance is actually achieved by a combination of different traits, of which succulence is only one. For example, traits related to leaves and roots (e.g. leaf area and size, leaf hairs or waxes, root length, root water content), seedling biomass and photosynthetic pathway, all contribute to a plant's tolerance to drought (see e.g.



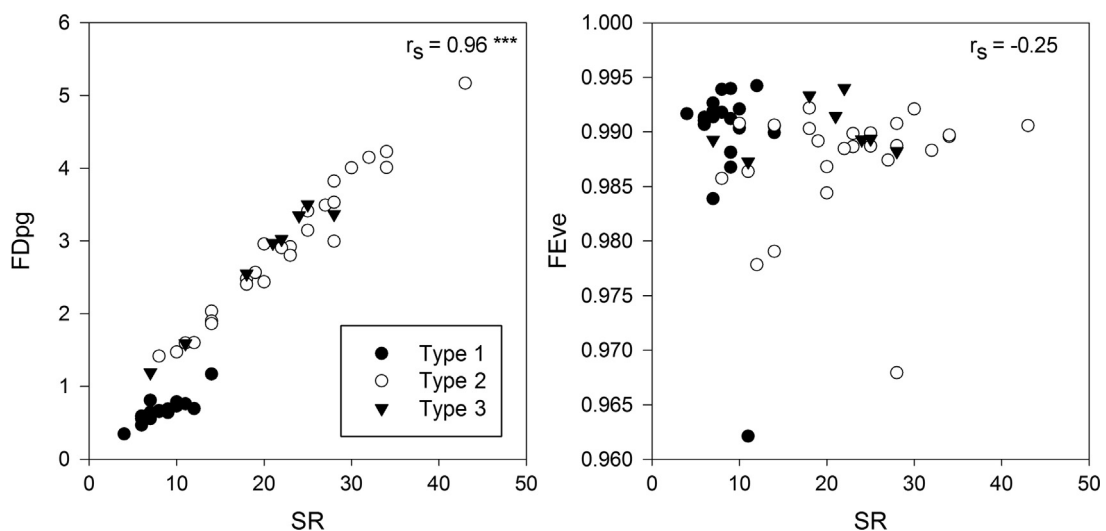
**Fig. 1.** Boxplots of the functional diversity indices FDpg and FEve for green roof Types 1–3 (*Sedum*, *Dianthus-Thymus* and *Linaria-Galium* type respectively). Significance of differences was tested using Kruskal–Wallis tests (\*\* $p \leq 0.05$ ; \*\*\* $p \leq 0.001$ ) and post hoc test results are expressed by letters (a, b, ab) above the boxes.

Cook-Patton & Bauerle, 2012; Markesteijn & Poorter, 2009; Van Mechelen, Dutoit, Kattge, & Hermy, 2014). We only considered plant traits related to green roof ecosystem services as found in the literature on green roofs, but still multiple traits related to drought tolerance were included in the FD analysis (e.g. leaf area, leaf phenology, photosynthetic pathway). So next to opting for succulents and hence drought tolerant species (trait convergence strategy), selecting plants that differ in their traits can also contribute to a drought tolerant vegetation. The trade-off between systems with succulents and the more species-rich and diverse systems should be considered carefully and placed in the context of the main purpose and construction limitations of the respective design project.

#### 4.2. Considerations for further research

Advantages of the FD approach are that it accounts for trait value complementarity between species, that diversity is measured at all hierarchical scales and that the resulting values are continuous (Petchey & Gaston, 2002). Although being a valuable diversity measure (Hooper et al., 2005; Mouchet et al., 2010; Petchey et al., 2004),

there might also be some limitations when applied to specific examples. The used green roof systems for instance only provided information on the initial species presence/absence, but not their relative abundance and vegetation dynamics once installed on a roof. This information would have resulted in more detailed clustering results and it would have affected the calculated FD and the FD maximization procedures (FDMax1 and FDMax2). However, this limitation does not fundamentally alter the approach adopted here, as for species selection for designing urban green elements, one often starts from simple species lists. Adding species that establish spontaneously and that have potential to increase the FD of the green roof system is an interesting option. Nevertheless, more research is needed in order to ensure that those additional species will be successful on green roofs in the long term, as they are not considered ‘tried-and-true’ as the other species present in the initial green roof systems. Another limitation regards the plant trait values, which were not available for species varieties and cultivars. The species lists of the green roof systems were thus reduced to the species level, therefore possibly causing some information loss as plant traits inevitably show some variability (cf. De Bello et al., 2011). Also, as indicated by the % missing values in



**Fig. 2.** Scatterplot of the relation between species richness (SR) for every green roof system and the functional diversity values FDpg and FEve. Green roof systems are grouped into green roof Types 1–3 (*Sedum*, *Dianthus-Thymus* and *Linaria-Galium* type respectively). Spearman Rank Correlation coefficients ( $r_s$ ) and significance are indicated (\*\*\*) ( $p \leq 0.001$ ).

Table 1, it was impossible to find specific trait information for certain species. Therefore, further trait screening of plant species and their intraspecific taxa is essential (cf. Pakeman, 2014).

The scientific evidence that biodiversity, species functional traits and their phylogenetic relationships are linked with ecosystem properties is increasing (Cardinale et al., 2012; Hooper et al., 2005; Isbell et al., 2011; Lavorel et al., 2011; Pinto et al., 2014; Quijas et al., 2012). Whether this also fully applies for novel urban ecosystems has not yet been proven, as the literature on FD and its effects on ecosystem properties of for example green roofs is still very limited. Lundholm et al. (2010) focused on summer roof cooling and water capture and concluded that these services can be improved by combining different life forms. However, for some ecosystem services (e.g. roof cooling), species-poor green roof systems outperformed the ones with high diversity, hence stressing the need for further investigation of biodiversity-ecosystem functioning relationships in green roof ecosystems (Lundholm et al., 2010). Furthermore, our study showed that green roof systems with high FD are also the ones that require deeper substrates. This result is in line with findings of Madre et al. (2014), who pointed at an important role of substrate depth on green roof plant diversity. Next to substrate depth, also substrate type (e.g. the water holding capacity or amount of organic matter) and local green roof variables (e.g. age and roof height) can also greatly influence the vegetation composition in the long term, hence influencing the FD (Madre et al., 2014). So further research is needed to elucidate the relative contribution of substrate and green roof properties to the FD of the green roof system and linked to that, the provisioning of ecosystem services.

Next to FD, phylogenetic diversity (PD) is considered a valuable proxy for FD (Gasc et al., 2013) because it accounts for species evolution and hence encompasses many additional and often unmeasured traits that may be important to determine ecosystem functioning (Cadotte, Cavender-Bares, Tillman, & Oakley, 2009; Srivastava, Cadotte, MacDonald, Marushia, & Mirotchnick, 2012). PD was measured as well for the green roof systems, following the methodology presented in Supporting information 1D. As results are similar to the observations made with the FD approach, and FD and PD proved to be highly significantly correlated, the results of the PD approach are not part of this manuscript, but can be found in Supporting information 2. The debate about which component of biodiversity influences ecosystem properties the most is still going on (Gasc et al., 2013; Hooper et al., 2005), so the compilation of the optimized species lists could have been based on both FD and PD. However, because of the many unresolved relationships, the resolution of the phylogenetic tree was not fine enough to use the evolutionary information for this analysis.

#### 4.3. Recommendations for urban ecosystem design

The two proposed methods, delivering an exact species list (FDMax1) and a more practical one that offers alternative species (FDMax2), illustrate how current urban green roof systems can be adapted to maximize FD and presumably also the overall ecosystem services. The focus of this study was on green roofs, but the methods are generic and offer a framework for improved design of a broad range of novel ecosystems, particularly in an urban context. For a new project, whether that be for instance, abandoned industrial sites, agricultural remnants, parks or gardens, one could start from an inventory of the species, eventually supplemented with potential interesting species considered for introduction on the site and then follow the approach adopted here. Clustering can yield insight into available or desired vegetation types. Next, databases should be consulted for relevant traits of the plant species, representing the range of desired ecosystem properties, after which FD analysis (eventually per vegetation type) will provide insights on

the ecological properties. The application of FDMax1 and FDMax2 will then indicate the most optimal species combination in terms of ecosystem services. It is also possible to focus the approach on plant traits that relate to a specific ecosystem service and therefore select plant species that maximize this service (cf. Lundholm & Richardson, 2010; Perring et al., 2013).

The approach adopted in this study only focused on FD and how we can use this measure to optimize species selection for green roof purposes. We acknowledge that as more empirical research becomes available, other possibilities may arise that also offer ways to improve species selection for green roofs, for example by looking at specific plant traits that are related to one or multiple ecosystem services. Also, the FD maximization methods proposed in this study should be interpreted with caution, as green roofs with high FD will only offer optimal ecosystem services when the initial high plant trait diversity can be maintained. This however, is not guaranteed, as some scientific studies indicate a decline in species richness of the green roof over time (e.g. Lundholm, Heim, Tran, & Smith, 2014; Rowe, Getter, & Durhman, 2012). Despite the number of current drawbacks of the FD approach, this study offers a way to design green roofs with high plant trait diversity. It also highlights that currently available extensive green roof systems differ greatly in their FD.

## 5. Conclusions

Extensive green roof systems, as model examples of novel urban ecosystems, offer a variety of ecosystem services. We assumed that ecosystem properties and services are positively correlated with functional diversity (FD). FD analysis highlighted that species-rich extensive green roof systems offer higher FD than the commonly used *Sedum* type. Two methods are proposed that both maximize FD and can be used for improved design of these novel ecosystems. These result in optimal species lists, an 'exact' one with the maximally possible FD and a practical list that also offers alternatives. The approach is generic and can thus also be used for other novel ecosystems, in particular urban green elements. It also offers the possibility to target specific ecosystem properties or services. By carefully considering species that maximize FD, the design of urban green infrastructure elements can become a more sustainable and vital tool to improve urban life quality.

## Acknowledgements

The authors are grateful to the KU Leuven and the Agency for Innovation by Science and Technology (IWT) for funding of respective C.V.M. and K.V.M. with a PhD scholarship.

## References

- Billionnet, A. (2013). Solution of the generalized Noah's Ark Problem. *Systematic Biology*, 62(1), 147–156. <http://dx.doi.org/10.1093/sysbio/sys081>
- Cadotte, M. W., Cavender-Bares, J., Tillman, D., & Oakley, T. H. (2009). Using phylogenetic, functional and trait diversity to understand patterns of plant community productivity. *PLoS ONE*, 4, e5695. <http://dx.doi.org/10.1371/journal.pone.0005695>
- Cardinale, B. J., Duffy, J. E., Gonzalez, A., Hooper, D. U., Perring, C., Venail, P., et al. (2012). Biodiversity loss and its impact on humanity. *Nature*, 486, 59–67. <http://dx.doi.org/10.1038/nature11148>

- Carter, T., & Jackson, C. R. (2007). Vegetated roofs for stormwater management at multiple spatial scales. *Landscape and Urban Planning*, 80, 84–94. <http://dx.doi.org/10.1016/j.landurbplan.2006.06.005>
- Chiesura, A. (2004). The role of urban parks for the sustainable city. *Landscape and Urban Planning*, 68(1), 129–138. <http://dx.doi.org/10.1016/j.landurbplan.2003.08.003>
- Cook-Patton, S. C., & Bauerle, T. L. (2012). Potential benefits of plant diversity on vegetated roofs: A literature review. *Journal of Environmental Management*, 106, 85–92. <http://dx.doi.org/10.1016/j.jenvman.2012.04.003>
- Cornelissen, J. H. C. (1996). An experimental comparison of leaf decomposition rates in a wide range of temperate plant species and types. *Journal of Ecology*, 84(4), 573–582. <http://dx.doi.org/10.2307/2261479>
- Couplan, F. (Ed.). (2009). *Le régal végétal. Plantes sauvages comestibles*. Paris: Editions Sang de Terre.
- Dakin, K., Benjamin, L. L., & Pantiel, M. (2013). *The professional design guide to green roofs*. London: Timber Press.
- De Bello, F., Lavorel, S., Albert, C. H., Thuiller, W., Grigulis, K., Dolezal, J., et al. (2011). Quantifying the relevance of intraspecific trait variability for functional diversity. *Methods in Ecology and Evolution*, 2, 163–174. <http://dx.doi.org/10.1111/j.2041-210X.2010.00071.x>
- Dufrêne, M., & Legendre, P. (1997). Species assemblages and indicator species: The need for a flexible asymmetrical approach. *Ecological Monographs*, 67(3), 345–366. <http://dx.doi.org/10.2307/2963459>
- Fitter, A. H., & Peat, H. J. (1994). The ecological flora database. *Journal of Ecology*, 82, 415–425. <http://dx.doi.org/10.2307/2261309>
- Gamfeldt, L., Snäll, T., Bagchi, R., Jonsson, M., Gustafsson, L., Kjellander, P., et al. (2013). Higher levels of multiple ecosystem services are found in forests with more tree species. *Nature Communications*, 4(1340), 1–8. <http://dx.doi.org/10.1038/ncomms2328>
- Gasc, A., Sueur, J., Jiguet, F., Devictor, V., Grandcolas, P., Burrow, C., et al. (2013). Assessing biodiversity with sound: Do acoustic diversity indices reflect phylogenetic and functional diversities of bird communities? *Ecological Indicators*, 25, 279–287. <http://dx.doi.org/10.1016/j.ecolind.2012.10.009>
- Gaston, K. J., Avila-Jiménez, M. L., & Edmondson, J. L. (2013). Managing urban ecosystems for goods and services. *Journal of Applied Ecology*, 50, 830–840. <http://dx.doi.org/10.1111/1365-2664.12087>
- Getter, K. L., & Rowe, D. B. (2006). The role of extensive green roofs in sustainable development. *HortScience*, 41, 1276–1285. <http://hortsci.ashspublications.org/content/41/5/1276.full.pdf>
- Hobbs, R. J., Arico, S., Aronson, J., Baron, J. S., Bridgewater, P., Cramer, V. A., et al. (2006). Novel ecosystems: Theoretical and management aspects of the new ecological world order. *Global Ecology and Biogeography*, 15, 1–7. <http://dx.doi.org/10.1111/j.1466-822x.2006.00212.x>
- Hobbs, R. J., Higgs, E., & Hall, C. M. (Eds.). (2013). *Novel ecosystems: Intervening in the new ecological world order*. UK: John Wiley and Sons.
- Hooper, D. U., Chapin, F. S., Ewel, J. J., Hector, A., Inchausti, P., Lavorel, S., et al. (2005). Effects of biodiversity on ecosystem functioning: A consensus of current knowledge. *Ecological Monographs*, 75, 3–35. <http://www.jstor.org/stable/4539083>
- Isbell, F., Calcagno, V., Hector, A., Connolly, J., Harpole, W. S., Reich, P. B., et al. (2011). High plant diversity is needed to maintain ecosystem services. *Nature*, 477, 199–202. <http://dx.doi.org/10.1038/nature10282>
- Kembel, S. W., Cowan, P. D., Helmus, M. R., Cornwell, W. K., Morlon, H., Ackerly, D. D., et al. (2010). Picante: R tools for integrating phylogenies and ecology. *Bioinformatics*, 26, 1463–1464. <http://dx.doi.org/10.1093/bioinformatics/btq166>
- Kleyer, M., Bekker, R. M., Knevel, I. C., Bakker, J. P., Thompson, K., Sonnenschein, M., et al. (2008). The LEDA Traitbase: A database of life-history traits of the Northwest European flora. *Journal of Ecology*, 96, 1266–1274. <http://dx.doi.org/10.1111/j.1365-2745.2008.01430.x>
- Kowarik, I. (2011). Novel urban ecosystems, biodiversity, and conservation. *Environment Pollution*, 159, 1974–1983. <http://dx.doi.org/10.1016/j.envpol.2011.02.022>
- Kühn, I., Durka, W., & Klotz, S. (2004). BIOLFLOR – a new plant-trait database as a tool for plant invasion ecology. *Diversity and Distributions*, 10, 363–365. <http://dx.doi.org/10.1111/j.1366-9516.2004.00106.x>
- Laliberté, E., & Shipley, B. (n.d.). *Measuring functional diversity (FD) from multiple traits, and other tools for functional ecology*. Package FD 1.0-11. Retrieved from <http://cran.at-r-project.org/web/packages/FD/FD.pdf>
- Lavorel, S., Grigulis, K., Lamarque, P., Colace, M.-P., Garden, D., Girel, J., et al. (2011). Using plant functional traits to understand the landscape distribution of multiple ecosystem services. *Journal of Ecology*, 99, 135–147. <http://dx.doi.org/10.1111/j.1365-2745.2010.01753.x>
- Lundholm, J. T., Heim, A., Tran, S., & Smith, T. (2014). Leaf and life history traits predict plant growth in a green roof ecosystem. *PLoS ONE*, 9(6), e101395. <http://dx.doi.org/10.1371/journal.pone.0101395>
- Lundholm, J. T., MacIvor, J. S., MacDougall, Z., & Ranalli, M. (2010). Plant species and functional group combinations affect green roof ecosystem functions. *PLoS ONE*, 5, 1–11. <http://dx.doi.org/10.1371/journal.pone.0009677>
- Lundholm, J. T., & Richardson, P. J. (2010). Mini-review: Habitat analogues for reconciliation ecology in urban and industrial environments. *Journal of Applied Ecology*, 47, 966–975. <http://dx.doi.org/10.1111/j.1365-2664.2010.01857.x>
- Madre, F., Vergnes, A., Machon, N., & Clergeau, P. (2014). Green roof as habitats for wild plant species in urban landscapes: First insights from a large-scale sampling. *Landscape and Urban Planning*, 122, 100–107. <http://dx.doi.org/10.1016/j.landurbplan.2013.11.012>
- Markestijn, L., & Poorter, L. (2009). Seedling root morphology and biomass allocation of 62 tropical tree species in relation to drought- and shade-tolerance. *Journal of Ecology*, 97, 311–325. <http://dx.doi.org/10.1111/j.1365-2745.2008.01466.x>
- Mason, N. W. H., Mouillot, D., Lee, W. G., & Wilson, J. B. (2005). Functional richness, functional evenness and functional divergence: The primary components of functional diversity. *Oikos*, 111, 112–118. <http://dx.doi.org/10.1111/j.0030-1299.2005.13886.x>
- McCune, B., & Mefford, M. J. (Eds.). (1999). *PC-ORD. Multivariate analysis of ecological data, Version 4. USA: MjM Software Design*.
- Mouchet, M. A., Villegier, S., Mason, N. W. H., & Mouillot, D. (2010). Functional diversity measures: An overview of their redundancy and their ability to discriminate community assembly rules. *Functional Ecology*, 24, 867–876. <http://dx.doi.org/10.1111/j.1365-2435.2010.01695.x>
- Oberndorfer, E., Lundholm, J. T., Bass, B., Coffman, R. R., Doshi, H., Dunnett, N., et al. (2007). Green roofs as urban ecosystems: Ecological structures, functions, and services. *BioScience*, 57, 823–833. <http://dx.doi.org/10.1641/b571005>
- Oudolf, P., & Kingsbury, N. (Eds.). (2013). *Planting: A new perspective*. London: Timber Press.
- Pakeman, R. J. (2014). Functional trait metrics are sensitive to the completeness of the species' trait data? *Methods in Ecology and Evolution*, 5, 9–15. <http://dx.doi.org/10.1111/2041-210X.12136>
- Paradis, E., Bolker, B., Claude, J., Cuong, H. S., Desper, R., Durand, B., et al. (n.d.). *Analyses of Phylogenetics and Evolution. Package Ape 3.1-1*. Retrieved from <http://cran.r-project.org/web/packages/ape/ape.pdf>
- Perring, M. P., Manning, P., Hobbs, R. J., Lugo, A. E., Ramalho, C. E., & Standish, R. J. (2013). Chapter 38: Novel urban ecosystems and ecosystem services. In R. J. Hobbs, E. S. Higgs, & C. M. Hall (Eds.), *Novel ecosystems: Intervening in the new ecological world order* (pp. 310–325). UK: John Wiley and Sons.
- Petchey, O. L., & Gaston, K. J. (2002). Functional diversity (FD), species richness and community composition. *Ecology Letters*, 5, 402–411. <http://dx.doi.org/10.1046/j.1461-0248.2002.00339.x>
- Petchey, O. L., Hector, A., & Gaston, K. J. (2004). How do different measures of functional diversity perform? *Ecology*, 85, 847–857. <http://dx.doi.org/10.1890/03-0226>
- Pinto, R., de Jonge, V. N., & Marques, J. C. (2014). Linking biodiversity indicators, ecosystem functioning, provision of services and human well-being in estuarine systems: Application of a conceptual framework. *Ecological Indicators*, 36, 644–655. <http://dx.doi.org/10.1016/j.ecolind.2013.09.015>
- Quijas, S., Jackson, L. E., Maass, M., Schmid, B., Raffaelli, D., & Balvanera, P. (2012). Plant diversity and generation of ecosystem services at the landscape scale: Expert knowledge assessment. *Journal of Applied Ecology*, 49, 929–940. <http://dx.doi.org/10.1111/j.1365-2664.2012.02153.x>
- R Core Team (n.d.). *R: A language and environment for statistical computing*. R Foundation for Statistical Computing, Vienna, Austria. Retrieved from <http://www.R-project.org/>
- Robinson, S. L., & Lundholm, J. T. (2012). Ecosystem services provided by urban spontaneous vegetation. *Urban Ecosystems*, 15, 545–557. <http://dx.doi.org/10.1007/s11252-012-0225-8>
- Rowe, D. B., Getter, K. L., & Durhan, A. K. (2012). Effect of green roof media depth on Crassulacean plant succession over seven years. *Landscape and Urban Planning*, 104, 310–319. <http://dx.doi.org/10.1016/j.landurbplan.2011.11.010>
- Shipley, B. (1995). Structured interspecific determinants of specific leaf-area in 34 species of herbaceous angiosperms. *Functional Ecology*, 9, 312–319. <http://www.jstor.org/stable/2390579>
- Snodgrass, E. C., & McIntyre, L. (Eds.). (2010). *The green roof manual: A professional guide to design, installation and maintenance*. Portland: Timber Press Inc.
- Srivastava, D. S., Cadotte, M. W., MacDonald, A. M., Marushia, R. G., & Mirotnick, N. (2012). Phylogenetic diversity and the functioning of ecosystems. *Ecology Letters*, 15, 637–648. <http://dx.doi.org/10.1111/j.1461-0248.2012.01795.x>
- The Plant List (n.s.). *Version 1.1. Published on the Internet*. Retrieved from <http://www.theplantlist.org/>
- Tzoulas, K., Korpela, K., Venn, S., Yli-Pelkonen, V., Kazmierczak, A., Niemela, J., et al. (2007). Promoting ecosystem and human health in urban areas using Green Infrastructure: A literature review. *Landscape and Urban Planning*, 81, 167–178. <http://dx.doi.org/10.1016/j.landurbplan.2007.02.001>
- Van Mechelen, Dutoit, T., Kattge, J., & Hermy, M. (2014). Plant trait analysis delivers an extensive list of potential green roof species for Mediterranean France. *Ecological Engineering*, 67, 48–59. <http://dx.doi.org/10.1016/j.ecoleng.2014.03.043>
- Villegier, S., Mason, N. W. H., & Mouillot, D. (2008). New multidimensional functional diversity indices for a multifaceted framework in functional ecology. *Ecology*, 89, 2290–2301. <http://dx.doi.org/10.1890/07-1206.1>
- Wittinghill, L., Rowe, D., Schutzi, R., & Cregg, B. M. (2014). Quantifying carbon sequestration of various green roof and ornamental landscape systems. *Landscape and Urban Planning*, 123, 41–48. <http://dx.doi.org/10.1016/j.landurbplan.2013.11.015>
- Wolch, J. R., Byrne, J., & Newell, J. P. (2014). Urban green space, public health, and environmental justice: The challenge of making cities 'just green enough'. *Landscape and Urban Planning*, 125, 234–244. <http://dx.doi.org/10.1016/j.landurbplan.2014.01.017>
- Wolf, D., & Lundholm, J. T. (2008). Water uptake in green roof microcosms: Effects of plant species and water availability. *Ecological Engineering*, 33, 179–186. <http://dx.doi.org/10.1016/j.ecoleng.2008.02.008>