

Root traits influence stormwater performance in a green roof microcosm

By  
Garland Xie

A Thesis Submitted to Saint Mary's University, Halifax, Nova Scotia in Partial  
Fulfillment of the Requirements for the Degree of Master of Science in Applied  
Science

August 28, 2019, Halifax, Nova Scotia

Copyright Garland Xie, 2019

Approved: Dr. Jeremy Lundholm  
Supervisor

Approved: Dr. Clarissa Sit  
Committee Member

Approved: Dr. Allison Walker  
Committee Member

Approved: Dr. Claire Farrell  
External Examiner

Date: August 28, 2019

## Table of Contents

List of Figures .....	iii
List of Tables .....	v
Abstract .....	vi
Acknowledgements .....	vii
Introduction .....	1
Materials and Methods .....	9
Results .....	17
Discussion .....	19
Conclusion.....	28
Figures .....	29
Tables .....	36
References .....	39

## List of Figures

**Figure 1.** Pairwise comparisons plot of the influence of species identity on mean water loss (mL). Point estimates indicate estimate least-squares mean for a given species, blue bands for 95% confidence intervals and red arrows for Tukey’s adjusted comparisons among groups. Here, if an arrow from one mean overlaps an arrow from another group, this suggests a statistically unclear” difference between both groups. The response variable was back transformed for ease of interpretation. ....29

**Figure 2.** Pairwise comparisons plot of the influence of species identity on mean water capture (mL). Point estimate indicate estimate least-squares mean for a given species, blue bands for 95% confidence intervals and red arrows for Tukey’s adjusted comparisons between groups. Here, if an arrow from one mean overlaps an arrow from another group, this suggests a “statistically unclear” difference between both groups. The response variable was back transformed for ease of interpretation. ....30

**Figure 3.** A conditional scatterplot of the influence of mean evapotranspiration on mean water capture in each watering regime treatment (wet, dry). ....31

**Figure 4.** A principal component analysis biplot of multiple functional traits for the dry condition. Note that the first two principal axes are shown. ....32

## List of Figures (Continued)

**Figure 5.** A principal component analysis biplot of multiple functional traits for the wet condition. Note that the first two principal axes are shown. ....33

**Figure 6.** A multi-panel figure comprised of multiple dot-and-whisker plots that summarizes the relationship between mean water loss and root traits for each watering regime treatment: A) dry, and B) wet. Points estimates represent standardized ordinary least-squares regression coefficients of each trait. Interval estimation represent 95% confidence intervals. ....34

**Figure 7.** A multi-panel figure comprised of multiple dot-and-whisker plots that summarizes the relationship between mean water capture and root traits for each watering regime treatment: A) dry, and B) wet. Points estimates represent standardized ordinary least-squares regression coefficients of each trait. Interval estimation represent 95% confidence intervals. ....35

## List of Tables

**Table 1.** Life-history information of each focal species used in this study. ....36

**Table 2.** Summary table of average root functional trait values (and standard deviations) of all focal species under each water regime treatment (i.e., wet, dry) .....37

# Root traits influence stormwater performance in a green roof microcosm

By  
Garland Xie

## **Abstract**

Water uptake from vegetation can govern plant productivity through different mechanisms in natural terrestrial ecosystems. However, the ability of plants to regulate water can be viewed as an ecosystem service in urban regions, where vegetation in constructed ecosystems can help reduce stormwater runoff through their root systems. However, there is no knowledge on how root traits operate in extensive green roofs, an increasingly popular form of green infrastructure, as the substrate environment has an extremely shallow substrate depth (~20 cm) and a lack of biological legacy. In this study, I found that stormwater performance is not solely a function of rooting depth; rather, a multitude of belowground traits govern water regulation in this novel ecosystem that may optimize transport capacity, soil exploration and root construction costs. Overall, this study parallels findings from natural ecosystems and provides practitioners with new tools to create a more functional green roof.

August 28 2019

## **Acknowledgments**

I would like to first thank my research supervisor, Jeremy Lundholm, for his unwavering support and insight into developing this project. Through an inclusive and positive learning environment, he allows his students to thrive in an academic setting through constructive feedback, thoughtful discussions and encouragement on work-life balance. I feel eternally grateful to have this opportunity to be a member of the Ecology of Plants in Communities Lab at Saint Mary's University, Halifax and I will strive to carry on this passion for urban ecological research onto the next phase of my career. I would also like to thank my committee members, Clarissa Sit and Allison Walker for their insightful feedback on my manuscript. Finally, I give thanks to my colleagues and staff in the Department of Biology: Caitlin Porter, Amy Heim, Hughstein Grimshaw-Surette, Emily Walker, Tasha Rabinowitz, Maddie Clarke, Jasmine Jamieson, Lindsay Burrell, Lyndsey MacDonald, Terrell Roulson, Bridgett Biermann, Tatsuya Matsuoka, Junyan Zhang, Ethan McNamara, Matt Logan, Carmen Cranley and Jing Yang.

My current success in academia is partly due to my research experience as an undergraduate in the Cadotte Urban Biodiversity and Ecosystem Services Lab at the University of Toronto Scarborough. I would like to acknowledge my previous research mentors for encouraging me to foster my curiosity in ecological research: Carlos Albertos Arnillas Merinas for quantitative ecology methods,

Marc Cadotte for ecosystem services, Stuart Livingstone for plant ecology, and finally Scott MacIvor for green roof ecosystems.

I give thanks all of the undergraduate volunteers who took time out of their busy schedules to help me in the data collection process: Ryan Ivany, Aisha Sowe, Ajay Radhakrishnan, Catlin Bradbury, Gloria D'Souza, Jillian Bellefontaine, Kayla Williams, Maka Ngulbe, Rebecca Lewis, Sahana Kanabar, Logan Cox, Sonha Drammeh and Jordan Davis.

The greatest thanks go to my family and best friends for providing unconditional support throughout my journey as an aspiring urban ecologist: Sherry Liu, Michael Xie, Leona Xie, Nicholas Sookhan, Jeya Venugopal, Jessica Lamando-Ohlsson, Michele Goh and Jasmine Wong Denike.

This research was funded in part by a Research Fellowship from the Department of Faculty Graduate Studies at Saint Mary's University, an NSERC CGS-M scholarship from the National Council of Research Canada, an NSGS scholarship by the Province of Nova Scotia, and a Clean Foundation Scholarship from the Clean Foundation Organization.



## Introduction

Water uptake is a critical process for global hydrological cycles across multiple terrestrial ecosystems (Canadell et al., 1996). The magnitude of water uptake depends on multiple interacting factors such as climate, local environmental conditions and plant vegetative strategies (Freschet et al., 2017). Such factors contribute non-trivial effects to the transpirational demand in the soil-plant-atmosphere continuum. For instance, the spatial configuration of plant root systems can impact evapotranspiration, which involves the transport of mobile water from the soil medium to the root zone during an active water potential gradient (Lynch, 1995). Because of this plant function, variation in water uptake directly links to overall plant productivity in several different settings such as agriculture (Comas et al., 2013), grasslands (Jesch et al., 2018) and forests (Forrester and Bauhus, 2016).

In urban regions, the ability for vegetation to influence hydrological processes in the soil medium can be viewed as an economically valuable ecosystem service, rather than solely as plant functioning (Cameron and Blanuša, 2016). For example, green infrastructure, including constructed ecosystems, are growing in popularity in cities partly because human designers can curate specific plant groups to provide regulating ecosystem services such as stormwater retention (reducing rainfall volumes from incoming stormwater floods) and rooftop cooling (via evapotranspiration) (Lundholm, 2015). In terms of city-scale water regulation, green infrastructure can encompass a variety of

different plant groups (i.e., grasses, forbs, succulents, and trees) that are installed to serve this importance service in different parts of the city (Prudencio and Null, 2018). For example, despite high spatial confinement, roots from urban street trees can create efficient conduit paths to allow incoming irrigation to infiltrate at a faster rate through the surrounding soil and thus mitigate any stormwater additions to traditional grey sewer systems (Bartens et al., 2008; Szota et al., 2019). Likewise, bioretention systems (“rain gardens”) share similar features to urban street trees, such as a high spatial boundary and ecological novelty, but instead incorporates rushes (family: *Juncaceae*) and sedges (family: *Cyperaceae*) to optimize stormwater mitigation (Payne et al., 2018).

In addition to urban street trees and bioretention cells, green roof ecosystems are a relatively untapped environmental resource for mitigating stormwater runoff (Oberndorfer et al., 2007). In more detail, green roofs house plants on a roof that consists of a vegetative layer, artificial retention layer, and engineered substrates. Based on substrate depth, green roofs come in two types: extensive green roofs with a maximum depth of 20cm, and intensive green roofs with possible depths of more than 20cm (Oberndorfer et al., 2007). In temperate climatic zones, the industry standard for vegetation includes species from the genus *Sedum* (family: *Crassulaceae*) since this plant group is remarkably drought-tolerant and can therefore thrive in the harsh roof conditions (i.e., little irrigation, high solar radiation, high wind speeds). For ideal hydrological performance, green roofs should retain as much water as possible following a

stormwater rainfall event, and then transpire it quickly, so that soil can accommodate more water during the next event (Sims et al., 2016).

Vegetation plays a critical role in green roof hydrological performance (Lambrinos, 2015). Human intervention is inherent to green roof design, and so certain stakeholders might wish to maximize the benefits of water regulation by carefully selecting the correct combinations of plants. Among all the drought-tolerant plants, species from the *Sedum* genus are not particularly adept at maximizing retention capacity because they tend to have low water requirements (Zhang et al., 2018). Moreover, finding the correct plant palette is time-consuming if the resulting species pool is quite large. To help circumvent these potential issues, selecting high performing plant life-form groups could be a reasonable start to optimize plant selection for stormwater management properties. Indeed, studies have shown that certain life-form groups vary in terms of stormwater capture and water loss - grasses and forbs often retain more stormwater than *Sedum* species, possibly due to a greater root growth in the green roof context (Nagase and Dunnett, 2012). However, even within a species, individuals can have high variation with respect to certain ecosystem processes (Cameron and Blanuša, 2016). Consequently, a finer-scale approach may be needed to tease apart the mechanisms between various ecological strategies and hydraulic performance in engineered ecosystems (Van Mechelen et al., 2014) .

As plant selection for constructed ecosystems is typically focused at the species level, interspecific variation in hydrological performance is important. This

variation is likely due to a subset of relevant functional traits, which are defined as phenotypic plant characteristics that are both measurable and linked to plant fitness (Violle et al., 2007) . Functional traits should be related to a given ecosystem process (i.e., evapotranspiration), and can encompass many morphological, anatomical, architectural and physiological ecological strategies. In contrast to plant life-form groups, incorporating functional traits into urban design is compelling because it offers both a fine-scale and generalizable approach to ecosystem service delivery (Cameron and Blanuša, 2016; de Bello et al., 2010). In other words, it bypasses taxonomic information or coarse categorization of plant life-forms and instead focuses on the appropriate contemporary ecological strategies required for a given service. In the context of green roofs, plant height and specific leaf area are two easily measurable aboveground functional traits that are linked to stormwater management properties. Here, tall plants with thin leaves were found to be correlated with net photosynthetic capacity, evapotranspirative rates and canopy interception, all of which are non-trivial contributions to retention capacity performance (Lundholm et al., 2015a).

While green roofs share similar features to unproductive natural ecosystems (e.g., tundra or dry grasslands), the belowground environment in this engineered ecosystem should be systematically different from their natural counterpart, which inadvertently influences how plant roots regulate water uptake. Broadly speaking, natural soil is seen as the “milieu of all belowground processes” (Holt, 2016) - roots of all shape and sizes from one species could

forage for essential resources (often through deep soil layers) and may interact with the roots from neighboring plant species. Further, plant roots tend to interact with other groups of organisms in shallow layers either as a beneficial (e.g., mycorrhizal fungi) or an antagonistic effect (e.g, soil pathogens). By contrast, constructed ecosystems do not initially possess this level of ecological complexity. Once built, extensive green roofs will have simplified features, such as a narrow biotope space (e.g., shallow substrate depths) and an engineered substrate that lacks any faunal ecological communities (Lundholm, 2015). Because of these highly engineered components, brought on by anthropogenic design, it's unclear as to how plant roots operate in such a unique urban environment, despite their critical role in water regulation.

With respect to natural ecosystems, root depth plays an important role in water regulation as deeper root depths allow for greater soil exploration for essential resources (Nippert and Holdo, 2015). In contrast, extensive green roof ecosystems are inherently bound to a maximum depth of only 20 cm or so. So, it is likely that root depth alone will not explain any variation in water uptake at all. In fact, most plants will grow their roots to a certain point and hit the bottom of the green roof system very quickly. Thus, an additional suite of below-ground traits is expected to drive the variation in water uptake in extensive green roof systems.

Beyond root depth, there could be other informative aspects of the belowground plant structure in green roof ecosystems that relate to water acquisition (Freschet and Roumet, 2017). Borrowing from the literature in natural

ecosystems, plant species exhibit fine roots (<2mm in diameter) that vary with respect to architecture and morphology. Here, the former term, root architecture, can be defined as the spatial configuration of the root system that exhibits a functional significance (Lynch, 1995). For example, maximum rooting depth can be viewed as vertical root distribution, as certain plant roots tend to navigate downwards to obtain unexplored patches of water. But plant can also expand their roots laterally to form a more complex structure, as a function of both root topology and root distribution, for soil exploration. Root length density, defined as the total root length per soil volume, could be used as a simple quantitative metric to help explain the relationship between root architecture and plant water-use (Fort et al., 2017). In the context of green roofs, there are currently no empirical studies that examine this particular trait, but there has at least been some discussion on the possible role of root density to drive stormwater capture. For example, it was observed that a higher root growth (and thus higher root density) from grass and forb species could have connected large aggregates in the soil in such a way the roots acted as a “water-retaining mat”, and thereby increasing stormwater capture (Nagase and Dunnett, 2012). By contrast, Maclvor et al (2011) found the opposite trend – similar life-form groups had low stormwater performance, in which the authors speculated that an increased root growth restricted pore size caused a decrease in stormwater capture. This set of mixed evidence could be demystified through the interplay between soil pore connectivity and root density (“preferential flow”) whereas a high root density results in a network of smaller pore sizes (Lange et al., 2009) impeding the flow

of mobile water travelling from the substrate surface to the bottom of the green roof system (Pérez-Harguindeguy et al., 2013).

Besides root architecture, the surface features of a single root axis (i.e., root morphology), as opposed to the entire root system, could provide additional variation in how root traits drive green roof stormwater performance. For example, the allocation of biomass to individual roots, variously described by the diameter of the root, root hairs, and their construction costs, can be summarized as the total root length per mass (e.g., specific root length). In particular, root diameter variation is thought to be important for water uptake, as larger roots may have a larger xylem channel that allow for a higher volume of water to enter the roots during transpirational demand, and thus facilitates the transport of water from the surrounding soil bulk medium to the roots (e.g., increased hydraulic conductivity) (Eissenstat, 2000; Kong et al., 2017). Currently, there is a lack of knowledge of the role of root diameter in green roofs. On other hand, certain plant species, at the individual root level, can invest in developing longer roots, at the cost of minimizing biomass, to optimize the chances of soil exploration and exploitation. Thus, this specific belowground strategy should allow for a higher water uptake across multiple terrestrial systems, including green roofs (Freschet and Roumet, 2017). To date, it was found that individual roots of *Sedum album* and *Sedum rupestre* can forage in the substrate medium, possibly for unexploited resource patches (Ji et al., 2018).

Lastly, the consideration of the size of a plant root system, relative to both plant shoot and leaves (i.e., fine-root mass fraction), could be an important trait related to soil water uptake. Here, plants may allocate a significant amount of resources among different organs to optimize resource acquisition. In particular, fine-root mass fraction can act as a surrogate for water uptake capacity, where plant individuals with high investment in belowground biomass production have either a denser root system, larger individual roots, higher specific root length, deeper roots, or an amalgam of all these traits, that partially contribute to water uptake (Comas et al., 2013). In green roofs, there is considerable interspecific variation in root mass fraction among grass, succulent and herb species (Farrell et al., 2013; Ji et al., 2018). Such trait variation suggests that root mass fraction could be directly linked to green roof ecosystem services, since it is expected that a greater investment in belowground ecological strategies should increase water uptake and thus improve water capture and evapotranspiration.

Here, the aim of this project was to conduct a green roof microcosm experiment to test if morphological and architectural traits influence two ecosystem services: stormwater capture (reducing stormwater runoff) and evapotranspiration (microclimatic cooling), in varying watering regimes (dry and wet). Specifically, I used twelve different drought-tolerant plant species, ranging from grasses, forbs and shrubs, that are known to survive on green roofs, as well as a soil-only control treatment. For these twelve species, I measured the following candidate root traits that are directly related to water acquisition (*sensu*



Freschet and Roumet, 2017) root length density, maximum rooting depth, fine root mass fraction, mean root diameter and specific root length.

## **Methods**

### *Plant selection*

Of the twelve species used in this study, I used nine native species (*Solidago bicolor* L., *Plantago maritima* L., *Symphyotrichum nolvi-belgii* (L.) G.L.Nesom, *Festuca rubra* (L.), *Danthonia spicata* (L.) Roem. & Schult, *Deschampia flexuosa* (L.) Trin, *Vaccinium macrocarpon* Aiton (1789), *Empetrum nigrum* L., *Sibbaldiopsis tridentata* (Sol.) Rydb; Table 1) that were collected in October 2017 from nearby local populations from coastal heathland ecosystems. I selected these species in a non-random fashion because of ease of propagation and association with shallow soils profiles similar to extensive green roofs (Lundholm, 2006). After collection, I stored the seed samples at 4°C until January 2018. I also collected cuttings from three exotic species in May 2018 (i.e., *Sedum acre* L., *Sedum album* L., *Sedum sexangulare* L.; Table 1), which are known to be popular in green roofs across Europe and North America. Cuttings were then transplanted to pots prior to the start of the experiment (see below).

### *Experimental design*

At the end of January 2018, I placed the seeds from nine native species in separate planting trays on a 5.1m X 1.3m bench in a green roof microcosm (glasshouse) located at Saint Mary's University in Halifax, Nova Scotia, Canada (44°39N, 63°35W). The native plants were grown for up to four months in the

planting trays under four eight fluorescent 32 W growth lights set to a 12-hr photoperiod (T8 Standard, Philips Lighting Holding BV, USA). For each tray, I watered them to field capacity (~ 1L of tap water) three times a week to ensure adequate germination and propagation.

Following the growth period, I transplanted four plant individuals from each native species to a pot (5.50 Kordlok Square Pot; 15 cm height X 13 cm width X 13 cm length). Each pot was filled with an industrial green roof substrate (Sopraflor X: Soprema Inc., Drummondville, QC, Canada) with a depth of 13 cm (~3.45 g). The composition of the green roof substrate contains a pH of 6.0–7.0, a total porosity of 60–70%, a bulk density of 1150–1250 kg/m<sup>3</sup> and lastly an organic matter (by dry weight) of 5–10%. For succulent species, I took cuttings from four individuals from a nearby green roof (Atrium Green Roof) and placed them in the appropriate pots a week after transplanting the native plant species. Overall, there was a total of twenty pots for each focal species (n = 9). In addition, twenty soil-only pots were included as a control treatment.

After two weeks, I removed three plants from each pot to prevent competitive interactions. Therefore, there were a total of ten pots (each with one plant individual) per species. Each pot was watered three times a week with tap water to field capacity prior to start of the experimental treatments (see below) to develop a mature root system as well as to minimize any confounding ontogenic effects (Ryser, 2006).

Prior to the start of the experiment in June 2018, I arranged all pots in a randomized block design with a total of five blocks. Each block contains ten pots (as plant individuals) of each twelve focal species (see above) and ten soil-only control pots for each watering regime treatment. Overall, there was a total of fifty-two pots in each block with a grand total of 260 pots across all blocks. Each block contains two experimental watering regime treatments: dry and wet condition.

To account for both edge effects and microclimatic conditions from surrounding plant canopies, I rotated all pots within a block each week over the experiment duration by moving two pots from the end of one row to the opposite end of the second row and shifting the rest down. In terms of watering regime, both treatments differ in the frequency of watering to each pot. The dry treatment indicates watering to field capacity every seven days and the wet treatment every four days.

### *Watering Regimes*

From June to September 2018, I used a simple water balance model to quantify stormwater capture and water loss in each treatment (Maclvor and Lundholm, 2011). Prior to the simulated rainfall events, I obtained an initial weight (T1) for every pot using an industrial scale (in grams). Afterwards, I slowly poured a liter of tap water over the base of the soil layer in each pot to achieve soil field capacity. I used extra caution for this step to ensure that the above-ground canopy did not intercept any incoming water. Then, I implemented a ten-minute wait time to remove any excess water from the pot. Afterwards, I took a second

weighing measurement for each pot (T2). I then took a third weighing at 48 hours (T3). Here, the difference between T1 and T2 indicates the amount of water captured from the rainfall event. Water loss between T3 and T2 was assumed to be lost via evapotranspiration as all water lost before T2 was assumed to be lost via runoff. Overall, I performed the simulated rainfall events for each experimental treatment at the appropriate intervals (every seven days for dry; every four days for wet) for a total of twelve weeks. Plants were then harvested at the end of the experiment (see below).

#### *Aboveground sampling*

To collect aboveground plant data, I followed a standardized protocol from previous literature (Pérez-Harguindeguy et al., 2013). For each plant individual, I first clipped all ramets 2-3 cm above the soil layer. Then, I subsequently oven-dried each plant sample for 48 hours at 60°C degrees to calculate the aboveground dry biomass (in grams). Note that I harvested species on different days based on their transpiration rates. I excluded any dead plant individuals from this process as well as from further trait measurements (see below).

#### *Root sampling*

Like above-ground sampling, I sampled roots at the end of the experiment (duration: July to September 2018). Here, I acknowledge that a single harvest method does not account for changes in root plasticity across time and individuals, which may present an additional confounding effect of plant size variation, as mature plants tend to have more developed root systems, such as a

higher root density (Ryser, 2006). Nevertheless, I opted out of this allometric approach of taking multiple plant harvests across a given growing season due to the logical constraints of having to deal with a larger sample size across all species.

To quantify the vertical root distribution, I measured maximum rooting depth using a ruler (in cm). I removed the soil from each individual pot by sifting any intact roots from a 500  $\mu\text{m}$  sieve. I gently removed any remaining soil from the roots by using a low flow of tap water. Finally, I sorted live and dead roots from the sample, and kept only living roots for further processing (Pérez-Harguindeguy et al., 2013).

Fine roots play a critical role in resource acquisition (McCormack et al., 2015). To obtain fine roots, I used a digital caliper on all harvested root samples to separate coarse roots from fine roots based on the traditional fine-root classification of < 2mm in diameter. Here, I do acknowledge that this threshold muddles the functional roles of fine roots based on root orders, such as transport and absorptive roots (McCormack et al., 2015). However, I opted for the traditional root classification framework instead due to the difficulty of finding the correct root branching hierarchy for the grass and sedum functional groups. Once the fine roots were separated, I cut each sample into 5-10 cm fractions and placed them into a container with a 70% ethanol-30% water solution. Finally, I placed all samples in a fridge (4°C) to preserve the samples until further processing (Pérez-Harguindeguy et al., 2013).

### *Root trait measurements*

To minimize root overlapping, I carefully placed each root sample in a plastic acrylic tray that was placed on top of a dual-light flatbed scanner (Epson Perfection V800). Due to the large size of certain samples (e.g., *Solidago bicolor*), I used multiple scans (with a resolution of 600dpi) to measure the total root length for each individual. I estimated the mean root diameter (mm) and total root length (mm) from the total scans of a given individual by using the IJ Rhizo software with the following set of parameters: excluded border of 50 pixels width, particle cleaning size of 1 mm<sup>2</sup>, circularity of particles of 0.75 (Pierret et al., 2013). Then, I oven-dried both set of fine (< 2mm) and coarse roots (>2 mm) at 60 °C for at least 48 hours to obtain the respective dry biomass weight (g). I measured the total specific root length (m g<sup>-1</sup>) as the total fine root length (comprising of all root orders) per dry biomass and root length density (cm cm<sup>-3</sup>) as the total fine root length per soil volume. I calculated total root biomass as the sum of both fine-root dry and coarse-root dry biomass (g). Lastly, I calculated fine-root mass fraction (g g<sup>-1</sup>) as the proportion of fine-root dry biomass per total plant dry biomass (as an allocation approach). Due to logistical constraints, I was not able to process all the root traits for *Festuca rubra*, *Symphyotrichum nolvi-belgii* and *Deschampia flexuosa*, and so these species were excluded from further statistical analyses (see below).

### *Statistical analysis*

All statistical analyses were done in R version 3.6.0 (Wang *et al.*, 2015; Kong *et al.*, 2017). To determine if different species vary in green roof

hydrological performance, I performed a two-way analysis of variance test, where the fixed effects were species identity (ten levels: including the soil-only control) and watering regime treatment (two levels: dry, wet) respectively. Here, the response variables are mean stormwater capture and mean water loss, which I log-transformed to stabilize the variance among groups. Due to unequal sample sizes for certain species (Table 2), I used a type II sum of squares as an omnibus test to account for the loss of orthogonality between the main effects of both explanatory variables (Hector et al., 2010). The results revealed a statistical difference among the groups in both species identity and watering regime for each ecosystem service ( $F_{9, 161} = 67.23$ ,  $p < 0.001$ ). Thus, for each response variable, I then conducted an adjusted Tukey's least-squares mean test for pairwise comparisons ( $\alpha = 0.05$ ) among different groups within a treatment using the "emmeans" package (Lenth, 2019).

I performed a principal component analysis using the `prcomp` function in the "stats" R package to understand the relationships between root length density, specific root length, mean root diameter, maximum rooting depth, total biomass, and fine-root mass fraction. As a pre-processing step, I standardized all candidate variables through mean centering and scaling to unit variance. The results are visualized as a PCA biplot from the "*factoextra*" R package for each watering regime treatment (Kassambara, 2016).

I performed a Pearson's product-moment correlation coefficient matrix prior to hypothesis testing to determine any effects of multicollinearity on the

following traits for each watering regime treatment (Dormann et al., 2013): root length density, specific root length, mean root diameter, maximum rooting depth, total plant biomass, and fine-root mass fraction. Preliminary results show that fine-root mass fraction and root length density were highly collinear ( $|r| > 0.7$ ) in both the dry and wet treatments. Thus, fine-root mass fraction as an explanatory variable was subsequently excluded from any further hypothesis testing, as root length density is a more ecologically relevant variable with respect to plant water resource uptake (Bodner et al., 2015; Fort et al., 2017).

To test if any candidate root traits influence green roof stormwater performance, I performed a hierarchical linear mixed-effect model using the *lme4* R package (Bates et al., 2007). Mean water loss and mean stormwater capture were chosen as response variables respectively, which were quantified as an average of all observations across the experimental period in all sampling units. For the set of explanatory variables, all functional roots traits (excluding plant biomass) were assigned as fixed effects, total plant biomass as a continuous covariate to account for plant size variation (Ryser, 2006), and lastly block as a random intercept-only effect.

All fixed effect variables were mean centered and scaled to unit variance (as z-scores) to interpret the estimated regression coefficients on a comparable scale (Schielzeth, 2010). Upon preliminary inspection, the variance component of the block random effect was zero. Due to singularity, I opted to drop the random-effect structure and used a multiple linear regression model instead. Diagnostic



regression plots were used to visually examine model adequacy by checking the assumptions of homogeneity of variance and normally distributed residuals. Here, any confidence intervals that overlap zero are interpreted as “statistically unclear”, with respect to the null hypothesis (Dushoff et al., 2019).

## Results

### *Interspecific variation in green roof stormwater performance*

As expected, there were differences in performance among the nine species. On average, across the entire sampling period, *Solidago bicolor* was the top performer for both ecosystem services, as it retained approximately 334% more stormwater (Figure 1) and lost the same relative amount of water (Figure 2) in both watering regime treatments, compared to the lowest set of performers (i.e., *Empetrum nigrum*, *Sedum acre*, *Vaccinium macrocarpon*, *Danthonia spicata*, *Sibbaldiopsis tridentata*). Using a similar comparison, *Plantago maritima* performed 80% better than the worst performers, followed by *Sedum sexangular* and *Sedum album* (56%), and lastly green roof substrate-only control and *Sibbaldiopsis tridentata* (32%). In addition, both ecosystem services (evapotranspiration and capture) were closely related (Figure 3) – evapotranspiration tends to drive water capture ( $\beta = 1.0$ , adjusted  $R^2 = 0.95$ ), albeit with a higher slope in dry conditions ( $\beta = 1.5$ ).

### *Differences in root traits among species*

The relationships between the candidate belowground traits are well-explained by the first two PCA axes for dry (Figure 4) and wet treatments (Figure 5). The first PCA axis from both treatments shows a gradient between highly productive species with fibrous root systems (i.e., *Solidago bicolor*, *Sedum sexangular*, *Sedum album*) to those with a lower root density and shallow root depth (i.e., *Sibbaldiopsis tridentata*, *Empetrum nigrum*, *Vaccinium macrocarpon*). In contrast, the second PCA axis contains information on a different set of traits in both treatments: species with high specific root length and low fine-root mass fraction (e.g., *Danthonia spicata*, *Sedum acre*) are differentiated from species with the opposite trait values. Overall, these results suggest the presence of consistent belowground trait syndromes regardless of changes in water availability.

### *Relationships between root traits and green roof ecosystem services*

After accounting for plant size variation, multiple functional root traits were found to be correlated with green roof ecosystem services across different watering regime treatments. Of the four root traits, root length density is positively correlated to both stormwater capture and evapotranspiration in the dry and wet treatments (Figure 6-7). In contrast, specific root length is negatively correlated with both ecosystem services (Figure 6-7). Moreover, the influence of mean root diameter on stormwater capture and evapotranspiration is statistically clear in the wet treatment, but not in the dry treatment (Figure 6-7). Lastly, the effect of

maximum rooting depth on both ecosystem services was statistically unclear (Figure 6-7).

## **Discussion**

### *Multiple root traits govern green roof hydrological performance*

Selecting plants to improve green hydrological performance is difficult because of a wide plant palette. Instead, a closer look at functional traits may be needed, especially from a belowground perspective, as roots are the primary plant organs responsible for regulating water uptake. In this study, across different water regime treatments, we found that species from different life-form groups vary in terms of stormwater performance, and that some root traits, but not all of them, influence stormwater capture and evapotranspiration in an extensive green roof ecosystem.

As expected, maximum rooting depth did not influence any stormwater management properties in this study. Here, the soil volume in extensive green roofs is limited to a vertical depth of only 10-15cm, compared to the deeper rooting space in tundra ecosystems (~50 cm, Poot and Lambers, 2008; Schenk, 2008). On the other hand, extensive green roof systems do share similar substrate depths to those of certain rock outcrops (i.e., ironstone communities in winter-wet shrublands (0 – 20 cm depth); (Lundholm and Walker, 2018). However, these rare ironstone species can exhibit adaptive root strategies (e.g., high early investments in roots, root system morphology) that allow for foraging

through the cracks in the rock to access water in deeper layers beyond the soil. Despite some similarities, extensive green roof ecosystems still offer a unique belowground environment, especially considering the strict spatial boundary. Here, many green roof species cannot develop deep roots to exploit or forage for essential resources, even under different environmental conditions. To illustrate, the roots of most of the focal species in this study, except for shrubs, hit the lower spatial boundary of 13 cm. Even with similar depth profiles, there is still an influence of interspecific variation on green roof hydrological performance (Figure 1,2). For instance, *Solidago bicolor* was the top performer for both ecosystem services as it captured 334% more water (and lost a similar amount) than the lowest performers such as *Sedum acre*, which corresponds with similar findings from a previous study on extensive green roof monocultures (Lundholm et al., 2015a). Independent of rooting depth, variation in other water transport capabilities, such as root length density or root diameter, could help explain such differences in performance (Freschet and Roumet, 2017). Taken together, our results lend further support that the quantification of root depth alone is insufficient to understand hydrological processes in water-limited ecosystems (Nippert and Holdo, 2015). Instead, the interplay of multiple belowground traits, should provide more insight into the role of belowground systems and water regulation in both constructed and natural ecosystems.

After accounting for plant size variation (as more mature plants tend to have more roots), root length density predicted both evapotranspiration and stormwater capture, which is in line with previous studies on water use relations

and belowground systems (Fort et al., 2017). A possible explanation could be that an increase in root length density allows for a greater exploration of soil resources, as well as increased contact length to mobile water in a given green roof module. Thus, in the event of transpirational demand, more water will be lost due to a higher root surface area, which should allow for a complete stormwater recharge event where a dry substrate can retain more incoming rainfall in the next stormwater event. Alternatively, species with a high root length density could interact with the soil structure to produce a network of micropore channels (i.e., preferential flow). Following this idea of pore connectivity, another possible mechanism could be that more roots would be in contact with mobile water (as infiltrating rainfall), leading a reduction of film thickness, and thus a reduced acceleration of water through the soil (higher stormwater performance) (Lange et al., 2009). However, I find that the focal green roof plant species that tend to transpire water quickly from the substrate also retain a lot of water in the next rainfall event (Figure 1-2, 7). While preferential flow was not directly tested in this study, this specific mechanism is unlikely a driving factor in stormwater performance. Rather, it seems like the relationship between root length density and water uptake is a result of exploiting a higher volume of soil resources with a greater root surface area, rather than the joint effects of root structure and pore connectivity.

With frequent inundation, species with a high root diameter and low specific root length, such as *Solidago bicolor*, seem to have an ideal trait combination to optimize both water capture and water loss in green roof

ecosystems. Where roots have access to more soil water resources, a large root diameter could be associated with a higher stele-to-cortex ratio, which results in a greater number of conduits per stele and thus a higher hydraulic conductivity (Eissenstat et al., 2000; Kong et al., 2017). Surprisingly, specific root length is independent of mean root diameter in this study, despite their inverse mathematical relationship with another root trait, root tissue density (Birouste et al., 2014). This lends some support to the notion of root trait dimensionality, where previous studies have found that specific root length is on a separate trait axis than root tissue density (Kramer-Walter et al., 2016). Here, I speculate that specific root length may be interpreted as providing orthogonal information such as root investment costs, as opposed to resource acquisition, in this ecosystem. In such a shallow soil profile, it could be that a large root diameter is more efficient at capturing water resources as a result of higher transport capacity, as opposed to the relationship between root fineness and resource acquisition (Fort et al., 2017). Overall, these findings imply that green roof plant species are not constrained in their root construction to acquire the appropriate resources.

Root morphology and architecture can improve stormwater performance and evapotranspiration by selecting plants with the appropriate functional traits (e.g., high root length density) to efficiently exploit the appropriate soil resources, but there may be a potential trade-off in such trait syndromes that could affect the magnitude of these ecosystem services. Broadly speaking, plant species should have biophysical constraints: resource-acquisitive species will likely have several different ecological strategies across different plant organs that enable them to

acquire mobile water quickly, but this could imply a possible liability in the form of low drought-tolerance (Reich, 2014). For example, in this study, *Solidago bicolor* was the top performer for both evapotranspiration and stormwater capture, while *Sedum acre* was among the poorest performing species (Figure 1, 2). In a previous green roof study, *Solidago bicolor* was less drought-tolerant than *Sedum acre*, *Danthonia spicata* and *Sibbaldiopsis tridentata* (Lundholm et al., 2014), which may be attributed to each of these species falling into opposite axes (i.e., resource-acquisitive, conservative) of the whole-plant economic spectrum (Reich, 2014). This suggests that *Solidago bicolor* may be a reasonable choice for short-term gains in stormwater performance on a green roof but may need to be paired with other species with a facilitative effect. For example, *Sedum* species can act as a “nurse plant” to cool the substrate for neighboring species (Butler and Orians, 2011), to help improve plant survival and regulatory ecosystem services in this water-limited ecosystem.

In this study, root morphology and architecture explained approximately 60% of the variation in the desired hydrological services. However, there may be other traits of interest that extend beyond these biological levels of organization. For example, initial planting schemes of extensive green roofs tend to have substrates that are depauperate in faunal belowground communities (Lundholm, 2015). Yet, mycorrhizal inoculation could facilitate root hydraulic conductivity through the production of extraradical hyphae, while also having the added benefit of minimizing the loading weight (Molineux et al., 2014). Furthermore, many of the focal species in this study are more than capable of forming a

symbiotic relationship with different mycorrhizal fungi, at least in natural ecosystems (John et al., 2017). Thus, including biotic traits, such as mycorrhizal colonization intensity as a continuous belowground trait, into an existing trait space could reveal additional, and possibly orthogonal, information on how below-ground systems govern green roof ecosystem services (Laughlin, 2014).

### *Belowground-aboveground linkages*

Plant height and specific leaf area are correlated with stormwater capture and rooftop cooling, respectively (Lundholm et al., 2015b). In this study, we found specific root length, root diameter and root length density influence both ecosystem services as well. However, root traits could be integrated with their leaf and canopy counterparts as belowground-aboveground linkages. Species that can transport water rapidly will likely have resource-acquisitive traits across all organ levels, and the reverse is also true for slow-growing species (Reich, 2014). For example, *Solidago bicolor* can capture large amounts of stormwater because this species is taller in stature and has a more fibrous root system than *Sedum acre*. On the other hand, there is mixed evidence that specific leaf area and specific root length are correlated with one another across multiple terrestrial ecosystems (Freschet et al., 2015; Kembel and Cahill, 2011). Such an inconsistent pattern suggests that a complex relationship between leaf and root traits could arise due to different selective pressures on the aboveground canopy (e.g., competition for light) and the belowground systems (e.g., soil freezing and thawing). Thus, it would be interesting to see if there were any consistent trait correlations across multiple plant organs in extensive green roof ecosystems.



### *Management Implications*

While plant species with a fibrous root system and large diameter are critical for improved stormwater regulation in green roof ecosystems, the measurement of such functional traits is an extremely time-consuming and laborious process. Nevertheless, this set of scientific information could be incorporated into a decision-support tool, along with other important ecological strategies (e.g., maximum plant height; Lundholm et al., 2015), that are readily available for interested stakeholders whose primary objective is to optimize stormwater capture and evapotranspiration on their green roofs. Following closely to a similar set-up for stormwater biofilter performance (Payne et al., 2018), such a tool could be adopted to green roofs that contain rough guidelines to quickly determine which indicators (as trait variation, e.g., high root length density) fall into a “low reliability predictor” or “high reliability predictor” category. Here, such categories indicate the expectation of a either a high performance or low performance species respectively. For example, *Solidago bicolor* could fall into the “high reliability predictor” section, where its indicators are tall plant height and a fibrous root system. In contrast, *Vaccinium macrocarpon* is expected to be placed in the “low reliability predictors” as its indicators are a tap root system with a short aboveground plant stature. Despite the possibility of high trait variation with species and individuals, the binary dichotomous nature of this tool could be a reasonable start to translate the link between functional traits and ecosystem processes into real-world application for green roof management.

### *Study Limitations*

While I do show that root traits impact hydrological performance on extensive green roofs, this study has substantial limitations. First, I only sampled root traits at the end of the experiment simply because of logistical constraints (Ryser, 2006). Because of this sampling method, I could not account for the confounding effects of any temporal changes in fine root variation (Comas et al., 2013). Second, this study is simplistic in design as there is an inherent lack of ecological interactions. It is important to note that most green roofs are not monocultures – stochastic events (e.g., seed dispersal from nearby urban green spaces), deliberate anthropogenic design (e.g., mixture plantings), or a combination of both, will introduce other plant species to form an ecological community (Lundholm, 2016). As a result, different species will inevitably interact with one another to acquire essential resources. With specific plant (and trait) combinations, this is particularly true when roots from one species could outcompete other species in terms of resource foraging or root growth, and may indirectly reduce both yield and ecosystem functioning (e.g., stormwater capture) relative to a single plant species with no competitive interactions. Our findings are therefore preliminary and generalizations on how roots traits link to green roof ecosystem services should be met with caution. Nevertheless, we demonstrate the potential that root traits could parallel the role of aboveground traits in predicting green roof ecosystem services (Lundholm *et al.*, 2015).

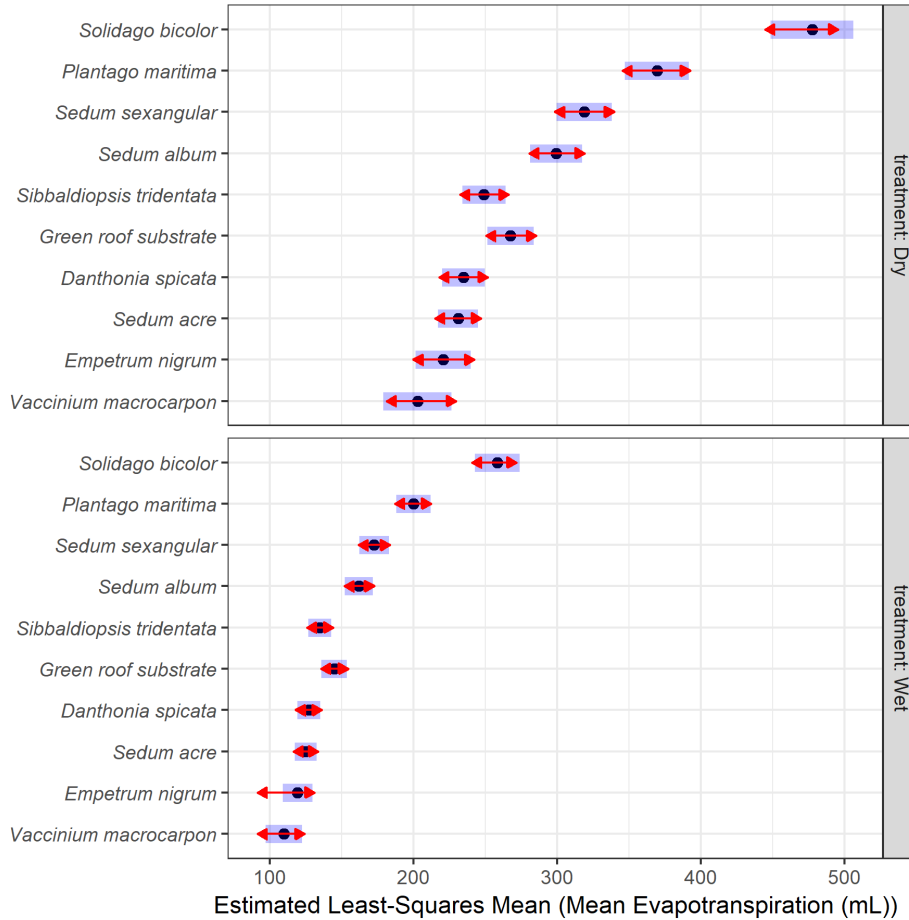
### *Future Research Directions*

In this study, there is evidence that show belowground traits are indeed important for the provisioning of green roof ecosystem services. However, green roofs are often assemblage of different species that interact with one another and other multitrophic organisms (e.g., mycorrhizal fungi). Future research is therefore required to further understand belowground interactions in green roof ecosystems. A good first step could be to simply study pairwise-interactions with different drought-tolerant species to determine how root traits of the most competitive species influence green roof ecosystem service, or if fungal traits from one species facilitates the growth of another. As a complementary approach, researchers could also quantify trait correlations among different plant organs (e.g., root, leaves) in order to uncover possible redundancies among belowground and aboveground traits. For example, plant height may be a good indicator for a high root length density if there is a high trait correlation across multiple species. Taken together, both future research avenues should provide practitioners with critical knowledge on selecting the most optimal plants to maximize stormwater performance objectives.

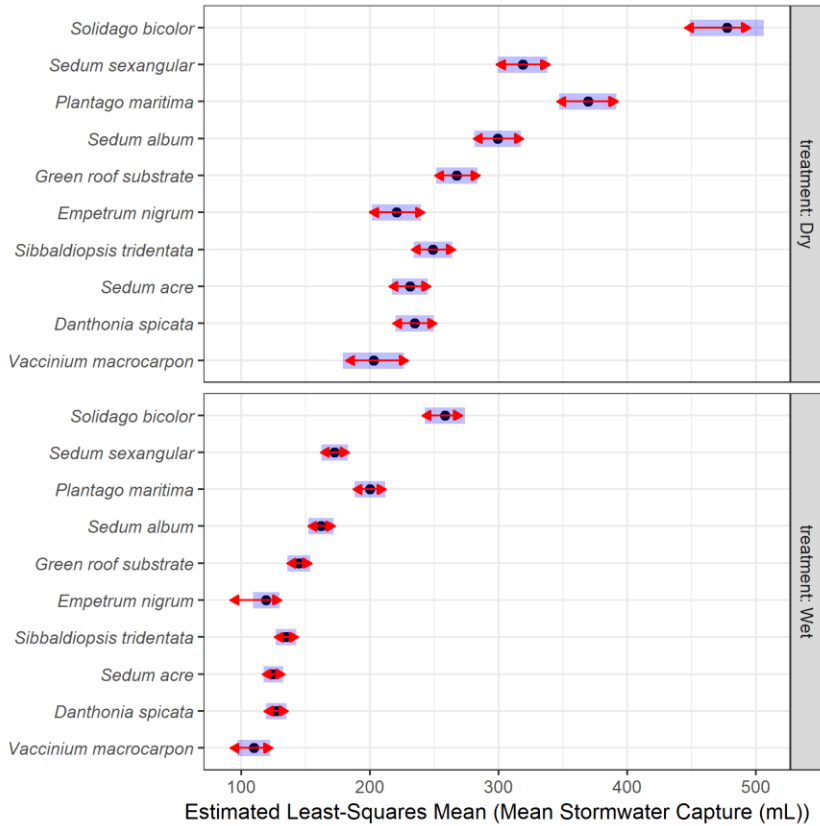
## **Conclusion**

The inclusion of functional traits in urban design may streamline the plant selection process for optimizing ecosystem services by providing a set of key plant strategies, including belowground root traits. Unlike their natural counterparts, constructed ecosystems have a unique substrate environment for how plant roots regulate water uptake, such as a strong spatial boundary, a lack of ecological legacy and a deliberate anthropogenic design. Here, we show that maximum rooting depth is not the sole predictor of stormwater retention and evapotranspiration in extensive green roof ecosystems. Rather, improving the performance of such services requires an additional suite of morphological and architectural belowground traits. From a non-random species pool, it seems that drought-tolerant plant species with a high density of large roots are the top performers for stormwater management properties. Overall, this study provides novel insight on how belowground systems impact water regulation in urban regions and may provide useful information for practitioners for maximizing green roofs.

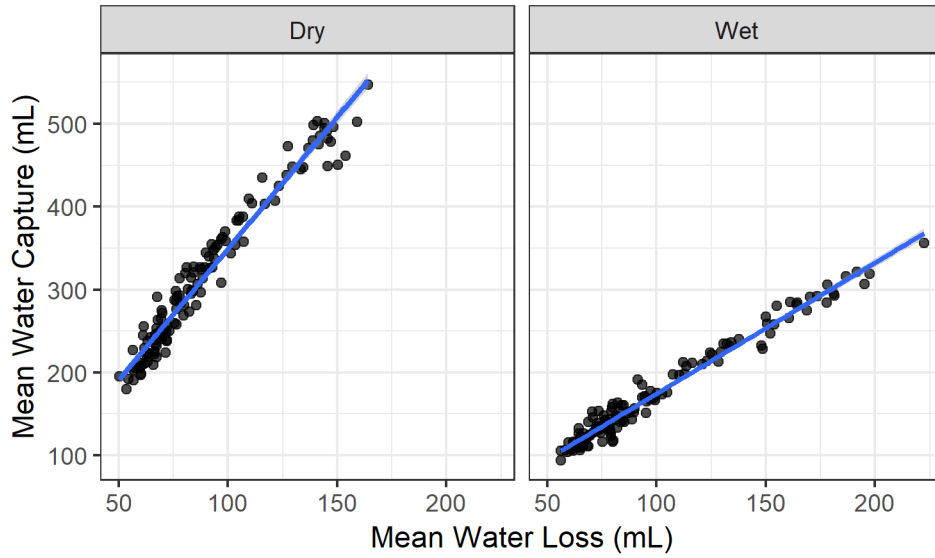
## Figures



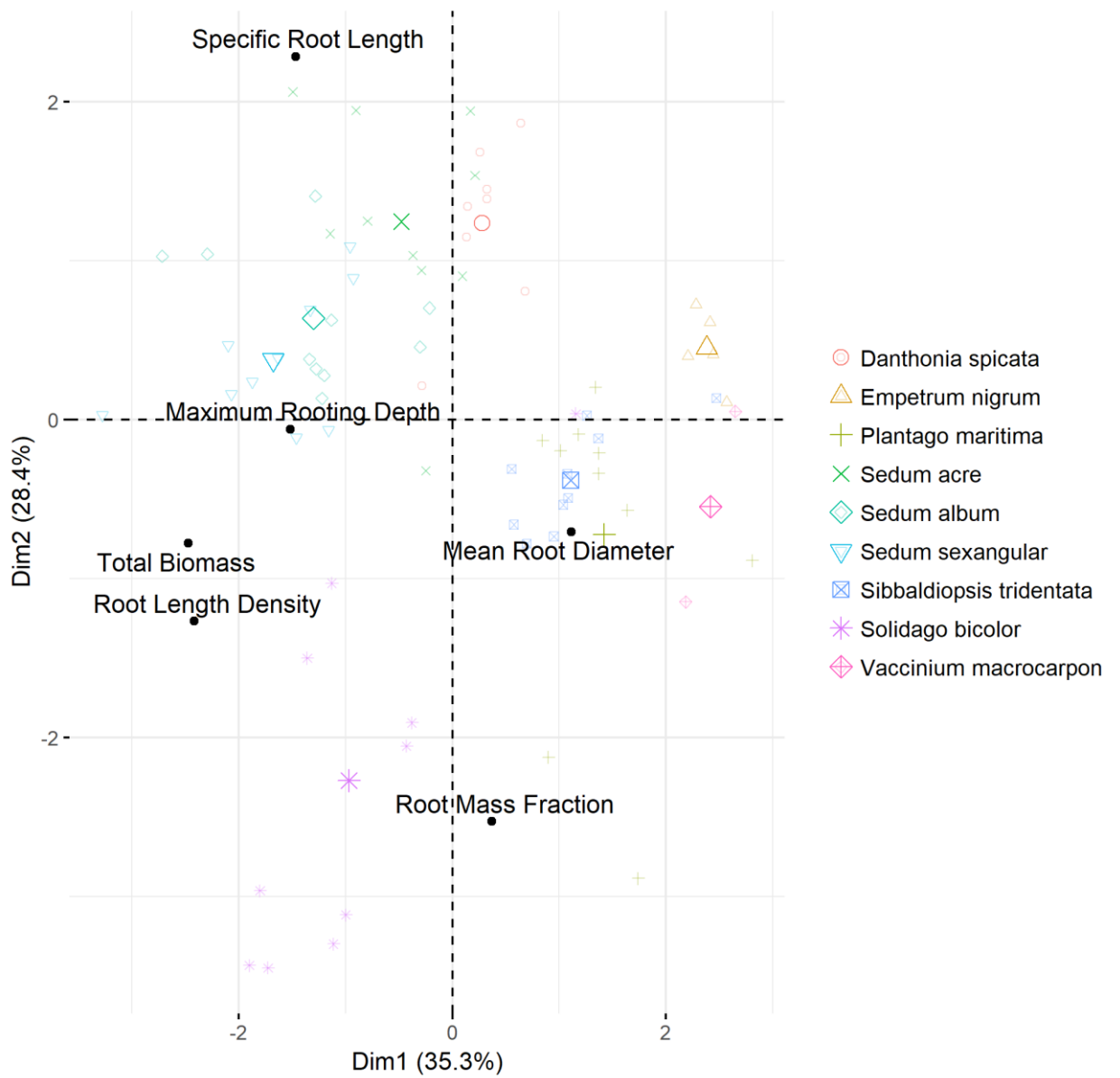
**Figure 1.** Pairwise comparisons plot of the influence of species identity on mean evapotranspiration (mL). Point estimates indicate estimate least-squares mean for a given species, blue bands for 95% confidence intervals and red arrows for Tukey’s adjusted comparisons among groups. Here, if an arrow from one mean overlaps an arrow from another group, this suggests a statistically unclear” difference between both groups (*sensu* Dushoff et al., 2019). The response variable was back-transformed from a log-transformation to raw values for ease of interpretation.



**Figure 2.** Pairwise comparisons plot of the influence of species identity on mean stormwater capture (mL). Point estimate indicate estimate least-squares mean for a given species, blue bands for 95% confidence intervals and red arrows for Tukey’s adjusted comparisons between groups. Here, if an arrow from one mean overlaps an arrow from another group, this suggests a “statistically unclear” difference between both groups (*sensu* Dushoff et al., 2019). The response variable was back-transformed from a log-transformation to raw values for ease of interpretation.

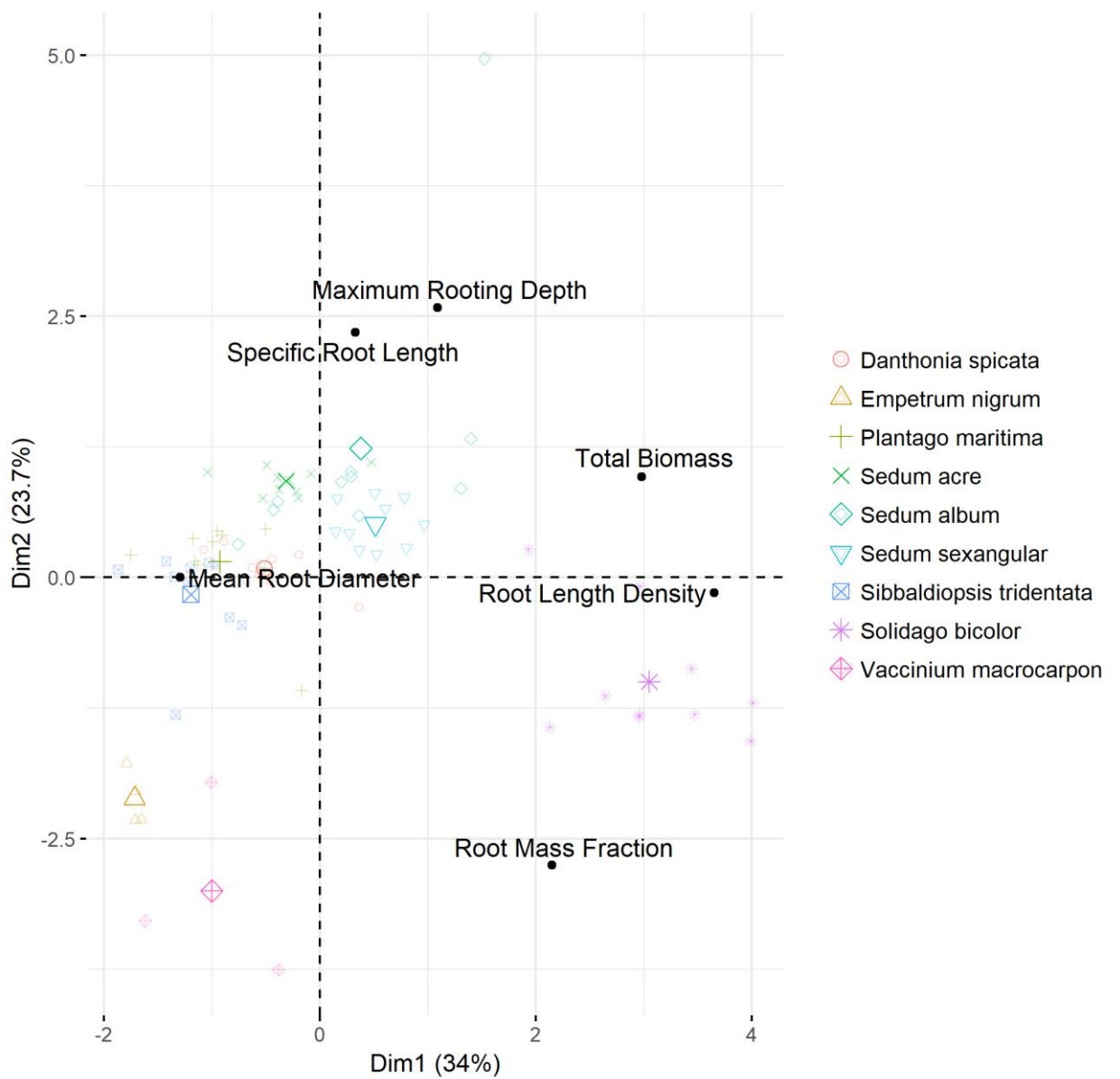


**Figure 3.** A conditional scatterplot of the influence of mean evapotranspiration on mean water capture in each watering regime treatment (i.e., wet, dry).

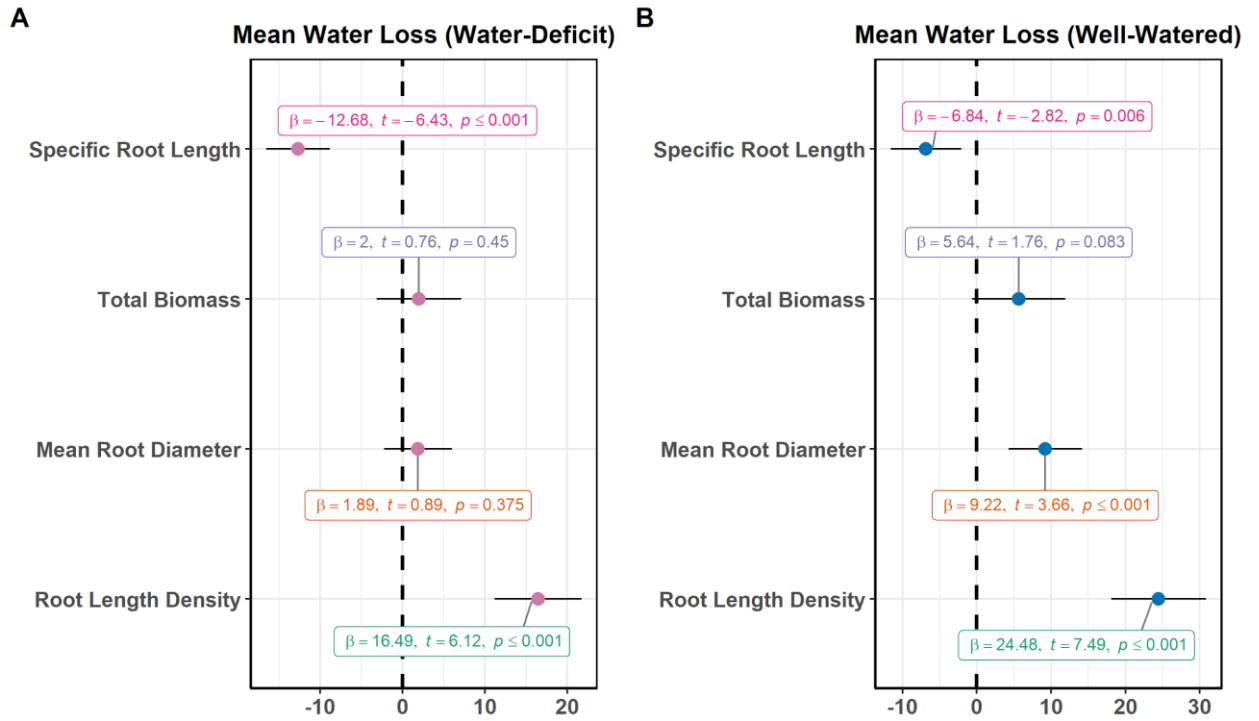


**Figure 4.** A principal component analysis biplot of multiple functional traits for the dry treatment. Note that only the first two principal axes are shown.

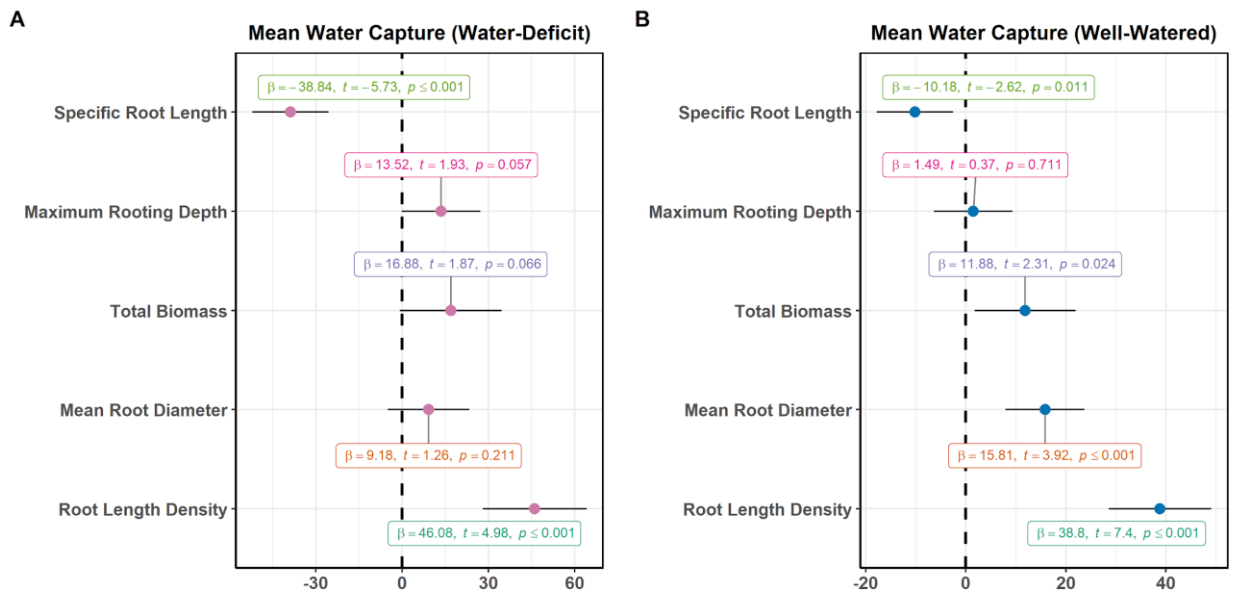




**Figure 5.** A principal component analysis biplot of multiple functional traits for the wet treatment. Note that only the first two principal axes are shown for this result.



**Figure 6.** A multi-panel figure comprised of multiple dot-and-whisker plots that summarizes the relationship between mean water loss and root traits for each watering regime treatment: A) dry, and B) wet. Points estimates represent standardized ordinary least-squares regression coefficients of each trait. Interval estimation represent 95% confidence intervals.



**Figure 7.** A multi-panel figure comprised of multiple dot-and-whisker plots that summarizes the relationship between mean water capture and root traits for each watering regime treatment: A) dry, and B) wet. Points estimates represent standardized ordinary least-squares regression coefficients of each trait. Interval estimation represent 95% confidence intervals.

## Tables

**Table 1.** Life-history information of each focal species used in this study.

Family	Genus	Species	Authority	Native	Growth-form
<i>Asteraceae</i>	<i>Symphyotrichum</i>	<i>novi-belgii</i>	(L.) G.L.Nesom	Native	Forb
<i>Plantaginaceae</i>	<i>Plantago</i>	<i>maritima</i>	L.	Native	Forb
<i>Asteraceae</i>	<i>Solidago</i>	<i>bicolor</i>	L.	Native	Forb
<i>Ericaceae</i>	<i>Vaccinium</i>	<i>macrocarpon</i>	Aiton (1789)	Native	Shrub
<i>Empetraceae</i>	<i>Empetrum</i>	<i>nigrum</i>	L.	Native	Shrub
<i>Rosaceae</i>	<i>Sibbaldiopsis</i>	<i>tridentata</i>	(Sol.) Rydb	Native	Shrub
<i>Crassulaceae</i>	<i>Sedum</i>	<i>album</i>	L.	Exotic	Succulent
<i>Crassulaceae</i>	<i>Sedum</i>	<i>acre</i>	L.	Exotic	Succulent
<i>Crassulaceae</i>	<i>Sedum</i>	<i>sexangular</i>	L.	Exotic	Succulent
<i>Poaceae</i>	<i>Festuca</i>	<i>rubra</i>	L.	Native	Graminoid
<i>Poaceae</i>	<i>Deschampia</i>	<i>flexuosa</i>	(L.) Trin.	Native	Graminoid
<i>Poaceae</i>	<i>Danthonia</i>	<i>spicata</i>	(L.) Roem. & Schult.	Native	Graminoid

**Table 2.** Summary table of average root functional trait values (and standard deviations) of all focal species under each water regime treatment (wet, dry condition). Abbreviations for species code: *Danthonia spicata* (DASP), *Empetrum nigrum* (EMNI), *Plantago maritima* (PLMA), *Sedum album* (SEAL), *Sedum acre* (SEAC), *Sedum sexangulare* (SESE), *Sibbaldopsis tridendata* (SITR), *Solidago bicolor* (SOBI), *Symphyotrichum novae-angliae* (SYNO), *Vaccinium macrocarpon* (VAMA). Trait values of *Symphyotrichum nolvi-belgii*, *Deschampia flexuosa* and *Festuca rubra* were excluded from this dataset due to logistical constraints

Treatment	Species Code	Sample Size	Root Length Density (cm/cm <sup>3</sup> )	Specific Root Length (m/g)	Total Plant Biomass (g)	Maximum Rooting Depth (cm)	Mean Root Diameter (mm)	Root Mass Fraction (g/g <sup>-1</sup> )
Dry	DASP	8	2.55 (2.55)	452.09 (52.06)	0.99 (0.64)	12.75 (0.71)	0.25 (0.04)	0.12 (0.04)
	EMNI	5	0.02 (0.01)	185.61 (41.66)	0.02 (0.01)	3.5 (0.61)	0.29 (0.04)	0.13 (0.03)
	PLMA	10	1.98 (1.18)	103.25 (49.88)	4.63 (2.17)	13 (0)	1 (0.38)	0.15 (0.15)
	SEAC	10	4.7 (2.62)	441.9 (179.57)	8.01 (4.15)	13 (0)	0.41 (0.06)	0.04 (0.02)
	SEAL	10	8.36 (2.83)	387.62 (121.68)	14.51 (4.38)	13 (0)	0.42 (0.05)	0.04 (0.02)
	SESE	10	13.44 (2.71)	414.61 (60.93)	12.89 (6.51)	12.4 (0.7)	0.33 (0.03)	0.07 (0.03)
	SITR	10	2.92 (1.7)	137.46 (21.32)	2.76 (1.45)	12.2 (2.53)	0.55 (0.11)	0.17 (0.03)
	SOBI	10	14.55 (6.48)	88.53 (24.71)	13.6 (4.76)	12.3 (0.82)	0.38 (0.03)	0.31 (0.12)

	VAMA	2	0.05 (0.07)	85.26 (39.84)	0.04 (0.03)	5.5 (3.54)	0.31 (0.1)	0.24 (0.15)
Wet	DASP	10	2.78 (2.37)	377.78 (72.54)	1.21 (0.6)	13 (0)	0.25 (0.04)	0.12 (0.05)
	EMNI	4	0.03 (0.03)	165.42 (93.07)	0.03 (0.01)	4.88 (0.75)	0.47 (0.09)	0.14 (0.01)
	PLMA	10	2 (1.45)	112.09 (73.19)	6.51 (2.12)	13 (0)	0.85 (0.22)	0.09 (0.09)
	SEAC	10	3.38 (1.73)	550.67 (115.48)	8.07 (4.06)	13 (0)	0.37 (0.07)	0.02 (0.01)
	SEAL	10	6.34 (4.9)	800.12 (1378.23)	14.24 (8)	12.6 (0.7)	0.44 (0.1)	0.02 (0.02)
	SESE	10	9.93 (2.73)	398.27 (61.99)	10.18 (2.09)	12.45 (0.76)	0.34 (0.07)	0.06 (0.02)
	SITR	10	1.08 (0.84)	119.94 (53.56)	1.7 (1.11)	12.6 (1.26)	0.68 (0.19)	0.11 (0.05)
	SOBI	10	22.33 (6.18)	89.41 (17.61)	16.92 (3.18)	12.8 (0.42)	0.38 (0.02)	0.38 (0.11)
	VAMA	3	0.04 (0.02)	234.67 (63.17)	0.01 (0.01)	4.73 (3.36)	0.36 (0.04)	0.35 (0.18)

## References

- Bartens, J., Day, S.D., Harris, J.R., Dove, J.E., Wynn, T.M., 2008. Can Urban Tree Roots Improve Infiltration through Compacted Subsoils for Stormwater Management? *J. Environ. Qual.* 37, 2048.  
<https://doi.org/10.2134/jeq2008.0117>
- Bates, D., Sarkar, D., Bates, M.D., Matrix, L., 2007. The lme4 Package. *October* 2, 1–6.
- Birouste, M., Zamora-Ledezma, E., Bossard, C., Pérez-Ramos, I.M., Roumet, C., 2014. Measurement of fine root tissue density: A comparison of three methods reveals the potential of root dry matter content. *Plant Soil* 374, 299–313. <https://doi.org/10.1007/s11104-013-1874-y>
- Bodner, G., Nakhforoosh, A., Kaul, H.P., 2015. Management of crop water under drought: a review. *Agron. Sustain. Dev.* 35, 401–442.  
<https://doi.org/10.1007/s13593-015-0283-4>
- Butler, C., Orians, C.M., 2011. Sedum cools soil and can improve neighboring plant performance during water deficit on a green roof. *Ecol. Eng.* 37, 1796–1803. <https://doi.org/10.1016/j.ecoleng.2011.06.025>
- Cameron, R.W.F., Blanuša, T., 2016. Green infrastructure and ecosystem services - is the devil in the detail? *Ann. Bot.* 118, 377–391.  
<https://doi.org/10.1093/aob/mcw129>
- Canadell, J., Jackson, R.B., Ehleringer, J.R., Mooney, H.A., Sala, O.E., Schulze, E.D., 1996. Max rooting depth of veg types at global scale Talks about boreal. *Oecologia* 108, 583–595. <https://doi.org/10.1007/BF00329030>

- Comas, L.H., Becker, S.R., Cruz, V.M. V., Byrne, P.F., Dierig, D.A., 2013. Root traits contributing to plant productivity under drought. *Front. Plant Sci.* 4. <https://doi.org/10.3389/fpls.2013.00442>
- de Bello, F., Lavorel, S., Díaz, S., Harrington, R., Cornelissen, J.H.C., Bardgett, R.D., Berg, M.P., Cipriotti, P., Feld, C.K., Hering, D., da Silva, P.M., Potts, S.G., Sandin, L., Sousa, J.P., Storkey, J., Wardle, D.A., Harrison, P.A., 2010. Towards an assessment of multiple ecosystem processes and services via functional traits. *Biodivers. Conserv.* 19, 2873–2893. <https://doi.org/10.1007/s10531-010-9850-9>
- Dormann, C.F., Elith, J., Bacher, S., Buchmann, C., Carl, G., Carré, G., Marquéz, J.R.G., Gruber, B., Lafourcade, B., Leitão, P.J., 2013. Collinearity: a review of methods to deal with it and a simulation study evaluating their performance. *Ecography (Cop.)*. 36, 27–46.
- Dushoff, J., Kain, M.P., Bolker, B.M., 2019. I can see clearly now: Reinterpreting statistical significance. *Methods Ecol. Evol.* <https://doi.org/10.1111/2041-210X.13159>
- Eissenstat, D.M., 2000. Linking Hydraulic Conductivity to Anatomy in Plants that Vary in Specific Root Length. *J. Am. Soc. Hortic. Sci.* 125, 260–264.
- Eissenstat, D.M., Wells, C.E., Yanai, R.D., Whitbeck, J.L., 2000. Building roots in a changing environment: implications for root longevity. *New Phytol.* 147, 33–42.
- Farrell, C., Szota, C., Williams, N.S.G., Arndt, S.K., 2013. High water users can be drought tolerant: using physiological traits for green roof plant selection. *Plant Soil* 372, 177–193. <https://doi.org/10.1007/s11104-013-1725-x>



- Forrester, D.I., Bauhus, J., 2016. A Review of Processes Behind Diversity—Productivity Relationships in Forests. *Curr. For. Reports* 2, 45–61.  
<https://doi.org/10.1007/s40725-016-0031-2>
- Fort, F., Volaire, F., Guilioni, L., Barkaoui, K., Navas, M.L., Roumet, C., 2017. Root traits are related to plant water-use among rangeland Mediterranean species. *Funct. Ecol.* 31, 1700–1709. <https://doi.org/10.1111/1365-2435.12888>
- Freschet, G.T., Roumet, C., 2017. Sampling roots to capture plant and soil functions. *Funct. Ecol.* 31, 1506–1518. <https://doi.org/10.1111/1365-2435.12883>
- Freschet, G.T., Swart, E.M., Cornelissen, J.H.C., 2015. Integrated plant phenotypic responses to contrasting above- and below-ground resources: Key roles of specific leaf area and root mass fraction. *New Phytol.* 206, 1247–1260. <https://doi.org/10.1111/nph.13352>
- Freschet, G.T., Valverde-Barrantes, O.J., Tucker, C.M., Craine, J.M., McCormack, M.L., Violle, C., Fort, F., Blackwood, C.B., Urban-Mead, K.R., Iversen, C.M., Bonis, A., Comas, L.H., Cornelissen, J.H.C., Dong, M., Guo, D., Hobbie, S.E., Holdaway, R.J., Kembel, S.W., Makita, N., Onipchenko, V.G., Picon-Cochard, C., Reich, P.B., de la Riva, E.G., Smith, S.W., Soudzilovskaia, N.A., Tjoelker, M.G., Wardle, D.A., Roumet, C., 2017. Climate, soil and plant functional types as drivers of global fine-root trait variation. *J. Ecol.* 105, 1182–1196. <https://doi.org/10.1111/1365-2745.12769>
- Hector, A., von Felten, S., Schmid, B., 2010. Analysis of variance with unbalanced data: An update for ecology & evolution. *J. Anim. Ecol.* 79, 308–

316. <https://doi.org/10.1111/j.1365-2656.2009.01634.x>
- Holt, R.D., 2016. Green roofs may cast shadows. *Isr. J. Ecol. Evol.* 62, 15–22.  
<https://doi.org/10.1080/15659801.2015.1118844>
- Jesch, A., Barry, K.E., Ravenek, J.M., Bachmann, D., Strecker, T., Weigelt, A., Buchmann, N., de Kroon, H., Gessler, A., Mommer, L., Roscher, C., Scherer-Lorenzen, M., 2018. Below-ground resource partitioning alone cannot explain the biodiversity-ecosystem function relationship: A field test using multiple tracers. *J. Ecol.* 2002–2018. <https://doi.org/10.1111/1365-2745.12947>
- Ji, P., Sæbø, A., Stovin, V., Hanslin, H.M., 2018. Sedum root foraging in layered green roof substrates. *Plant Soil* 1–14. <https://doi.org/10.1007/s11104-018-3729-z>
- John, J., Kernaghan, G., Lundholm, J., 2017. The potential for mycorrhizae to improve green roof function. *Urban Ecosyst.* 20, 113–127.  
<https://doi.org/10.1007/s11252-016-0573-x>
- Kassambara, A., 2016. Package ‘factoextra.’
- Kembel, S.W., Cahill, J.F., 2011. Independent evolution of leaf and root traits within and among temperate grassland plant communities. *PLoS One* 6, 12–15. <https://doi.org/10.1371/journal.pone.0019992>
- Kong, D., Wang, J., Zeng, H., Liu, M., Miao, Y., Wu, H., Kardol, P., 2017. The nutrient absorption–transportation hypothesis: optimizing structural traits in absorptive roots. *New Phytol.* 213, 1569–1572.  
<https://doi.org/10.1111/nph.14344>
- Kramer-Walter, K.R., Bellingham, P.J., Millar, T.R., Smissen, R.D., Richardson,

- S.J., Laughlin, D.C., Bellingham, P.J., Millar, T.R., Smissen, R.D., Richardson, S.J., Laughlin, D.C., 2016. Root traits are multidimensional: specific root length is independent from root tissue density and the plant economic spectrum. *J. Ecol.* 104, 1299–1310. <https://doi.org/10.1111/1365-2745.12562>
- Lambrinos, J.G., 2015. Water Through Green Roofs. [https://doi.org/10.1007/978-3-319-14983-7\\_4](https://doi.org/10.1007/978-3-319-14983-7_4)
- Lange, B., Lüscher, P., Germann, P.F., 2009. Significance of tree roots for preferential infiltration in stagnic soils. *Hydrol. Earth Syst. Sci.* 13, 1809–1821. <https://doi.org/10.5194/hess-13-1809-2009>
- Laughlin, D.C., 2014. The intrinsic dimensionality of plant traits and its relevance to community assembly. *J. Ecol.* 102, 186–193. <https://doi.org/10.1111/1365-2745.12187>
- Lenth, R., 2019. emmeans: Estimated Marginal Means, aka Least-Squares Means.
- Lundholm, J., Heim, A., Tran, S., Smith, T., 2014. Leaf and life history traits predict plant growth in a green roof ecosystem. *PLoS One* 9, e101395.
- Lundholm, J., Tran, S., Gebert, L., 2015a. Plant Functional Traits Predict Green Roof Ecosystem Services. *Environ. Sci. Technol.* 49, 2366–2374. <https://doi.org/10.1021/es505426z>
- Lundholm, J., Tran, S., Gebert, L., 2015b. Plant functional traits predict green roof ecosystem services. *Environ. Sci. Technol.* 49, 2366–2374. <https://doi.org/10.1021/es505426z>
- Lundholm, J.T., 2015. The ecology and evolution of constructed ecosystems as

- green infrastructure. *Front. Ecol. Evol.* 3, 106.  
<https://doi.org/10.3389/fevo.2015.00106>
- Lundholm, J.T., 2006. Green roofs and facades: a habitat template approach. *Urban Habitats* 4, 87–101.
- Lundholm, J.T., Walker, E.A., 2018. Evaluating the Habitat-Template Approach Applied to Green Roofs. *Urban Nat.* 39–51.
- Lynch, J., 1995. Root Architecture and Plant Productivity', *Plant Physiol.*
- Maclvor, J.S., Lundholm, J., 2011. Performance evaluation of native plants suited to extensive green roof conditions in a maritime climate. *Ecol. Eng.* 37, 407–417. <https://doi.org/10.1016/j.ecoleng.2010.10.004>
- Maclvor, J.S., Ranalli, M.A., Lundholm, J.T., 2011. Performance of dryland and wetland plant species on extensive green roofs. *Ann. Bot.* 107, 671–679.  
<https://doi.org/10.1093/aob/mcr007>
- McCormack, M.L., Dickie, I.A., Eissenstat, D.M., Fahey, T.J., Fernandez, C.W., Guo, D., Helmisaari, H.S., Hobbie, E.A., Iversen, C.M., Jackson, R.B., Leppälammil-Kujansuu, J., Norby, R.J., Phillips, R.P., Pregitzer, K.S., Pritchard, S.G., Rewald, B., Zadworny, M., 2015. Redefining fine roots improves understanding of below-ground contributions to terrestrial biosphere processes. *New Phytol.* 207, 505–518.  
<https://doi.org/10.1111/nph.13363>
- Molineux, C.J., Connop, S.P., Gange, A.C., 2014. Manipulating soil microbial communities in extensive green roof substrates. *Sci. Total Environ.* 493, 632–638. <https://doi.org/10.1016/j.scitotenv.2014.06.045>
- Nagase, A., Dunnett, N., 2012. Amount of water runoff from different vegetation

types on extensive green roofs: {Effects} of plant species, diversity and plant structure. *Landsc. Urban Plan.* 104, 356–363.

<https://doi.org/10.1016/j.landurbplan.2011.11.001>

Nippert, J.B., Holdo, R.M., 2015. Challenging the maximum rooting depth paradigm in grasslands and savannas. *Funct. Ecol.* 29, 739–745.

<https://doi.org/10.1111/1365-2435.12390>

Oberndorfer, E., Lundholm, J., Bass, B., Coffman, R.R., Doshi, H., Dunnett, N., Gaffin, S., Köhler, M., Liu, K.K.Y., Rowe, B., 2007. Green Roofs as Urban Ecosystems: Ecological Structures, Functions, and Services. *Bioscience* 57, 823–833. <https://doi.org/10.1641/B571005>

Payne, E.G.I., Pham, T., Deletic, A., Hatt, B.E., Cook, P.L.M., Fletcher, T.D., 2018. Which species? A decision-support tool to guide plant selection in stormwater biofilters. *Adv. Water Resour.* 113, 86–99.

<https://doi.org/10.1016/j.advwatres.2017.12.022>

Pérez-Harguindeguy, N., Díaz, S., Garnier, E., Lavorel, S., Poorter, H., Jaureguiberry, P., Bret-Harte, M.S., Cornwell, W.K., Craine, J.M., Gurvich, D.E., Urcelay, C., Veneklaas, E.J., Reich, P.B., Poorter, L., Wright, I.J., Ray, P., Enrico, L., Pausas, J.G., De Vos, A.C., Buchmann, N., Funes, G., Quétier, F., Hodgson, J.G., Thompson, K., Morgan, H.D., Ter Steege, H., Van Der Heijden, M.G.A., Sack, L., Blonder, B., Poschlod, P., Vaieretti, M. V., Conti, G., Staver, A.C., Aquino, S., Cornelissen, J.H.C., 2013. New handbook for standardised measurement of plant functional traits worldwide. *Aust. J. Bot.* 61, 167–234. <https://doi.org/10.1071/BT12225>

Pierret, A., Gonkhamdee, S., Jourdan, C., Maeght, J.L., 2013. IJ\_Rhizo: An

- open-source software to measure scanned images of root samples. *Plant Soil* 373, 531–539. <https://doi.org/10.1007/s11104-013-1795-9>
- Poot, P., Lambers, H., 2008. Shallow-soil endemics: Adaptive advantages and constraints of a specialized root-system morphology. *New Phytol.* 178, 371–381. <https://doi.org/10.1111/j.1469-8137.2007.02370.x>
- Prudencio, L., Null, S., 2018. Stormwater management and ecosystem services: a review. *Environ. Res. Lett.* <https://doi.org/10.1088/1748-9326/aaa81a>
- Reich, P.B., 2014. The world-wide “fast-slow” plant economics spectrum: A traits manifesto. *J. Ecol.* 102, 275–301. <https://doi.org/10.1111/1365-2745.12211>
- Ryser, P., 2006. The mysterious root length. *Plant Soil* 286, 1–6. <https://doi.org/10.1007/s11104-006-9096-1>
- Schenk, H.J., 2008. Soil depth, plant rooting strategies and species’ niches. *New Phytol.* 178, 223–225.
- Schielzeth, H., 2010. Simple means to improve the interpretability of regression coefficients. *Methods Ecol. Evol.* 1, 103–113. <https://doi.org/10.1111/j.2041-210X.2010.00012.x>
- Sims, A.W., Robinson, C.E., Smart, C.C., Voogt, J.A., Hay, G.J., Lundholm, J.T., Powers, B., O’Carroll, D.M., 2016. Retention performance of green roofs in three different climate regions. *J. Hydrol.* 542, 115–124. <https://doi.org/10.1016/j.jhydrol.2016.08.055>
- Szota, C., Coutts, A.M., Thom, J.K., Virahsawmy, H.K., Fletcher, T.D., Livesley, S.J., 2019. Street tree stormwater control measures can reduce runoff but may not benefit established trees. *Landsc. Urban Plan.* 182, 144–155. <https://doi.org/10.1016/j.landurbplan.2018.10.021>

- Van Mechelen, C., Dutoit, T., Kattge, J., Hermy, M., 2014. Plant trait analysis delivers an extensive list of potential green roof species for Mediterranean France. *Ecol. Eng.* 67, 48–59. <https://doi.org/10.1016/j.ecoleng.2014.03.043>
- Violle, C., Navas, M.L., Vile, D., Kazakou, E., Fortunel, C., Hummel, I., Garnier, E., Oikos, S., May, N., Violle, C., Navas, M.L., Vile, D., Kazakou, E., Fortunel, C., 2007. Let the concept of trait be functional! *Oikos* 116, 882–892. <https://doi.org/10.1111/j.2007.0030-1299.15559.x>
- Zhang, Z., Szota, C., Fletcher, T.D., Williams, N.S.G., Werdin, J., Farrell, C., 2018. Influence of plant composition and water use strategies on green roof stormwater retention. *Sci. Total Environ.* 625, 775–781. <https://doi.org/10.1016/j.scitotenv.2017.12.231>