EFFECT OF SUBSTRATE DEPTH AND TYPE ON PLANT GROWTH FOR EXTENSIVE GREEN ROOFS IN A MEDITERRANEAN CLIMATE

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ABSTRACT

Although numerous examples of green roofs can be found in Turkey, limited research has been conducted on plant material and substrate type in this climate. Both plants and substrate are very important components in green roof design, it is essential to determine the proper substrates and plants in green roof systems for domestic green roof design. Two types of growing substrates: a commercial substrate consisting of crushed brick and clay (45%), pumice (45%), and organic matter (10%), and a recycled substrate including 90% coarse pumice (10–20 mm) and municipal compost (10%), were tested in three depths of 4, 7 and 10 cm. Tested plant species included *Achillea millefolium*, *Armeria maritima*, *Sedum acre* and *Sedum album*. Overall, the commercial substrate performed better than the recycled pumice. In addition, deeper substrates promoted greater survival and growth for nearly all species tested. Either *A. maritima* or *A. millefolium* survived in the recycled pumice at any depth, whereas they did survive when grown in the commercial substrate in greater than 7 cm and 10 cm, respectively. They both likely would require supplemental irrigation to be acceptable for green roofs in Istanbul or locations with a similar climate. Both *Sedum* species survived in all substrate types and depths. Information gained can be utilized by green roof professionals in the Istanbul region and in other parts of the world with a similar climate.

KEYWORDS

extensive green roof, substrate depth, plant material, substrates, Istanbul

1. INTRODUCTION

Negative effects of urbanization and concerns related to global warming have resulted in increased interest in green roof applications and research activities around the world. Most research supports the positive effects of green roofs in the built-environment as they provide benefits such as storm water management (Berndtsson et al., 2006, Dunnett et al., 2008; Gregoire and Clausen, 2011, Eksi, 2013, Lim and Lu, 2016, Feitosa and Wilkinson, 2016),

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energy conservation (Eksi et al., 2017; Fioretti et al., 2010; Huang et al., 2016), mitigation of UHIE (Susca et al., 2011; Getter et al., 2011; McIvor et al., 2016), increased life of roofing materials (Porsche and Köhler, 2003; Liu and Baskaran, 2004), as well as aesthetic and social aspects (Yuen and Nyuk Hien, 2005; Fernandez-Cañero et al., 2013). Placing plants on rooftops present challenges to landscape architects and these challenges usually revolve around two main topics: plant selection and substrates (both type and depth).

There has been a trend to make green roofs more sustainable by localizing green roof systems to their surrounding climate by utilizing native plant species and substrate mixtures (Eksi and Rowe, 2016; MacIvor and Lundholm, 2011; Nagase and Dunnett, 2013; Savi et al., 2014, Kokkinou et al., 2016). In this context, Turkey has much potential due to its ecological location. Climatic conditions, availability of local materials, and plant species in Turkey differ from Northern European countries where these systems were born and developed. Climate conditions in Turkey are variable and range from the temperate warm Mediterranean climate found on the coastal regions (Köppen climate classification 'Csa' and 'Csb') characterized by dry hot summers to the inland Anatolia plateau (Köppen climate classification 'Bsk') that experiences a dryer climate with hot summers and cold winters with limited rainfall (Arnfield, 2009, Öztürk et al., 2017). The climate characteristics of Istanbul also show differences throughout the city. As stated by Ezber et al. (2007), the southern parts of provincial Istanbul show the general characteristics of the Mediterranean climate (Köppen climate classification 'Csa') while the climate northward is somewhat modified by the cooler Black Sea and northerly colder air masses of maritime and continental origins which is locally called 'the Black Sea Climate' (Köppen climate classification 'Cfa'). Turkey was divided into 30 specific flora regions (grids) by Davis (1965) that contain more than 10,000 species of plants. However, there is very limited knowledge and published research available about how these plants and various roof substrates will perform in this region, the A2 Zone (Marmara region where Istanbul is located) (Davis, 1965; TUBIVES, 2016). Therefore, it is critical to perform various research studies for successful domestic green roof applications.

Plant selection for extensive green roofs is crucial because these plants are often exposed to harsh environmental conditions on the roof. In a Mediterranean climate, these conditions are often even harsher due to drought periods in summer and absence of supplementary irrigation in extensive green roof systems. Due to their drought tolerance and regenerative abilities, *Sedum* species are commonly used in green roof applications. According to Farrell et al. (2012), under severe drought substrates with higher water holding capacity, plant survival could be extended up to 12 days and Sedum species could live 15 days longer due to their conservative water consumption abilities.

Despite dry periods during summer, the wide variety of plant species and climatic conditions of Istanbul brings some opportunities and challenges to designers. Generally accepted green roof guidelines are based on research performed in Northern countries, especially in Germany (FLL, 2008), and those recommendations are not always applicable in a region with climates such as Istanbul, especially for unirrigated green roof systems due to longer dry periods. Thus, there is a need for research to trial local species or substrate materials. Despite dry periods during summer, the wide variety of plant species and climatic conditions of Istanbul brings some opportunities and challenges to designers. Generally accepted green roof guidelines are based on research performed in Northern countries, especially in Germany (FLL, 2008), and those recommendations are not always applicable in a region with climates such as Istanbul, especially for unirrigated green roof systems due to longer dry periods. Thus, there is a need for research

to trial local species or substrate materials. Several studies have investigated plant selection and substrate mixtures on green roofs in Mediterranean or similar climate conditions in the USA and Australia where plants experience frequent drought and heat stress on unirrigated roofs. Within the hot, humid, subtropical climate of Texas, Dvorak et al. (2013a, 2013b) investigated survival of several plant species and concluded that green roofs in hotter climates could also be established by proper maintenance and using suitable plant species. In a similar climate in Australia, Farrell et al. (2013) evaluated twelve species indigenous to granite outcrops in south-eastern Australia. It was concluded that using these species in green roofs brings plasticity in terms of water use as they can survive periods of drought.

In addition, due to weight limitations, substrate depths should be limited, but reducing depth can have a strong negative influence on plant performance. Shallow substrates have lower water holding capacity (Dunnett et al., 2008; Berndtsson, 2010: VanWoert et al., 2005), are more subject to temperature variations (Boivin et al., 2001; Nardini et al., 2012, Eksi et al., 2017), and limits the root growth of plants (Getter and Rowe, 2006; Rowe et al., 2012). As substrate depth increases, water holding capacity increases along with the weight of the green roof system (Getter and Rowe, 2006) and it provides a better environment for the plant success (Durhman et al., 2007). In the subtropical climate of Auckland, NZ, where summers tend to be warm and humid, Fassman and Simcock (2012) reported that an extensive living roof with 70% v/v 4–10 mm pumice, 10% v/v 1–3 mm zeolite, and 20% organic matter, and a 100 mm depth is recommended to maintain plants without irrigation (excluding drought conditions). In addition, according to Dvorak et al. (2013b), 11.4-cm-deep expanded shale substrates can support the plants in dry periods in the hot, humid and subtropical climate of Texas.

In this study, microcosms (small, self-contained artificial plant communities) (Dunnett et al., 2008) are established on an open field on raised benches and specific measurements such as plant survival, plant growth index, volumetric moisture content of growing substrate, and root: shoot ratios. Two types of growing substrates were used for comparison of plant survival (commercial and local recycled material) in three depths of 4, 7 and 10 cm. Thus, the aim of the study was to explore some native plant species for use on green roofs, to implement recycled materials in green roof systems, and to examine the possibilities of using those materials as a growing substrate.

2. MATERIALS AND METHODS

The study was conducted at the Istanbul University Green Roof Research Project (IUGRS) site, located at the Northern part of Istanbul in Bahcekoy–Sariyer Region, 41.10°N, 28.59°E. The study area is located in a suburban area of Istanbul in the neighborhood of Belgrade Forest. Plastic crates measuring 60 × 80 cm (inner dimensions 55.5 × 75 cm) were placed on metal benches and each crate replicated a typical extensive green roof. Roofing layers were installed directly in the plastic crates and included moisture retention fleece (SSM45, Onduline Avrasya AS, Istanbul; Zinco Gmbh, Germany), a plastic drainage mat (Maxidrain 25, NetYapi, Istanbul), filter sheet (SF Filter Sheet, Onduline Avrasya AS, Istanbul; Zinco Gmbh, Germany), and growing substrate.

Crates were filled to depths of 4, 7 and 10 cm for each of the two different substrate blends, commercial and recycled substrate mixtures. The commercial substrate Zincolite (Onduline Avrasya A.S., Istanbul) consisted of crushed brick and clay (45%), pumice (45%) and organic matter (10%). The recycled substrate was hand mixed at the site and consisted of 90% coarse pumice (10–20 mm) and municipal compost (10%) produced from residential waste and litter at ISTAC (Istanbul Environmental Management Industries, Istanbul Metropolitan Municipality). All substrate blends were homogeneously mixed at the site and distributed to the crates. Substrate blends are designated as (B) and (P) for commercial brick-clay based and recycled pumice based substrates, respectively, in the study. Depth of the substrates was also designated by adding the number for depth after (B) or (P). Each treatment was replicated three times in a total of 18 crates randomly distributed among platforms plots. Each substrate was analyzed to determine granulometric distribution, bulk density, water-holding capacity, pH, soluble salts and nutrient content (Istanbul University Faculty of Forestry Soil Ecology Laboratory, Istanbul, Turkey (Figure 1 and Table 1).

Four native plant species were tested which included *Achillea millefolium*, *Armeria maritima*, *Sedum acre* and *Sedum album*. *Sedum acre* and *Sedum album* were obtained from Yesil Vadi Nursery (Tarabya, Istanbul) as plugs. Initial plant growth index (PGI) was calculated for each plant by measuring plant height and width in two directions to form a growth index [(L × W × W)/3] (Monterusso et al., 2005; Rowe et al., 2006) at the time of planting. *Achillea millefolium* seedlings were in 18 plastic pots (10 × 8 × 8 cm dimensions) and separated into three equal smaller seedlings at the site before planting (initial mean PGI 7.98 ± 1.28). *Armeria maritima* seedlings in plastic pots (9 × 6 × 8 cm dimensions) were divided into two portions and planted into crates (initial mean PGI 8.02 ± 1.40). *Sedum acre* (initial mean PGI 7.41 ± 1.53) and *Sedum album* (initial mean PGI 5.82 ± 1.09) seedlings were in flats (5.5 × 5.5 × 7 cm × 48/flat) and directly planted into the crates. Plugs were planted on 28 April 2015, 10.0 cm from platform edges with three plants in a row 18.0 cm apart. Each row was spaced 18.0 cm from another, resulting in 4 rows. Each plant species was planted three times randomly in each section. All plots were fertilized on the day of planting with Osmocote Exact, 15+9+11+2MgO+TE controlled release fertilizer (11 g/m^2; 6 grams per crate) and watered by hand until dripping occurred. Irrigation was continued for the next 15 days to aid in plant establishment. After this point, supplemental irrigation ceased and plants had to rely on natural rainfall.

FIGURE 1. Granulometric distribution of the substrate mixtures

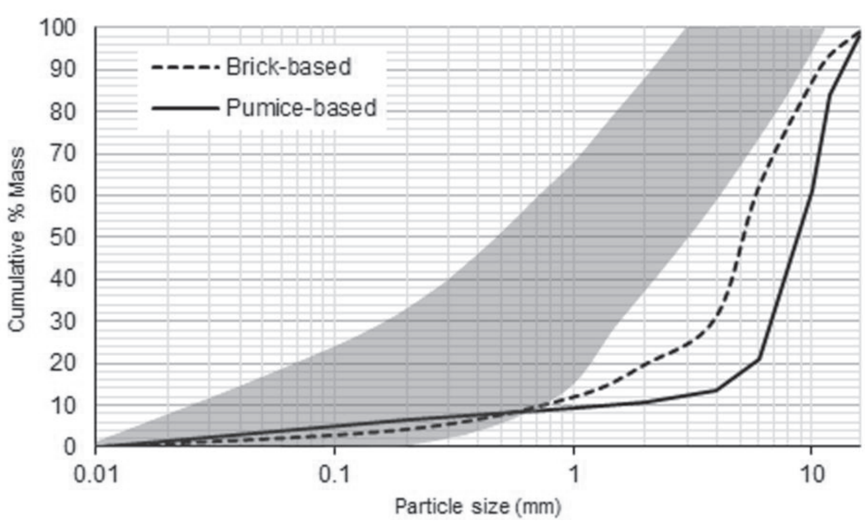


TABLE 1. Substrate physical and chemical properties at initiation of the study

Characteristic	Unit	Pumice-based Substrate (P)	Brick-based Substrate (B)	FLL[a] Guidelines
Bulk Density (dry weight basis)	g/L	458.26	812.90	—
Maximum WHC	Vol (%)	79.32	43.49	20–65
Nitrogen	mg/L	21.31	73.23	≤ 80 mg($CaCl_2$)/L
Organic carbon	Vol (%)	5.18	12.92	—
pH		7.55	7.64	6.0–8.5
Soluble Salts	g (KCl)/L	1.49	2.51	≤ 3.5 g (KCl)/L
Silt-Clay content	Mass (%)	6.50	4.30	<15% by Mass
Infiltration rate	mm/min	112.90	53.87	0.6—70

Analysis performed by Istanbul University Faculty of Forestry Soil Ecology Laboratory, Istanbul, Turkey. WHC stands for Water Holding Capacity.

[a] Forschungsgesellschaft Landschaftsentiwicklung Landschaftsbau (FLL), 2008. Guidelines for the Planning Execution and Upkeep of Green-Roof Sites. FLL Guidelines are for single course extensive green roofs

Each crate was set at 1% slope along with the benches below and a drainage hole was drilled from the lower side of the slope to allow excess water to drain. Substrate volumetric moisture content was measured on randomly selected days. Substrate moisture levels were recorded at four points in each plot by inserting a Theta probe (ML2x; Delta-T Devices, Ltd., Cambridge, UK) with 6.0 cm rods into the substrate. The Theta probe instrument has a range of 0.0–1.0 m^3m^{-3}, with accuracy of ±0.01 m^3m^{-3} for values from 0.05 to 0.6 m^3m^{-3}.

Weather data was continuously recorded at the study site by an automated weather station (DeltaOhm HD2003 Three Axis Ultrasonic Anemometer, Delta OHM S.r.L., Padova/Italy, measurement accuracy ±1°C) and precipitation measurements were collected using a rain gauge (DeltaOhm HD 2003 tipping bucket, measurement accuracy ±1%,). Climate norms of Istanbul between 1950 and 2015 (TMS Istanbul) were obtained from the Turkish State Meteorological Service National Weather Service.

Root and shoot biomass accumulation was measured by obtaining plant dry weights at the initiation and at the end of the study period. Initial dry weights were obtained from five representative samples of each plant species. Plants were removed from the substrate, separated into roots (below-ground) and shoots (above-ground), washed, and then dried for 144 hr. at 60°C (Farrell et al., 2012). The same procedure was applied to all plants at the end of the study. Biomass accumulation was calculated as the difference between the mean initial and final dry weights.

All data were checked for normality prior to analysis of variance by using the Kolmogorov-Smirnov test (Minitab, Inc., State College, PA). Significant differences among plots were analyzed by One-Way ANOVA tests using Fisher's LSD comparison (Little and Hills, 1978; Bousselot et al., 2011; Butler and Orians, 2011). Data transformation (the natural log transformation) was applied to biomass accumulation values to stabilize the variance and normalize the data set (Underwood, 1998). Original means are presented in the study. Data was analyzed using Minitab®16.2.2 (Minitab Inc., State College, PA) and Microsoft Excel® 2013.

3. RESULTS AND DISCUSSION

3.1 Weather conditions

During the 27 weeks of the study period (28 April 2015–14 October 2015), weather patterns were different from local TMS climate norms recorded between 1950 and 2015 (Turkish State Meteorological Service National Weather Service, 2015). Average ambient temperature of the study period was recorded as 19.5°C, which was 1.2°C higher than climate norms of Istanbul. The warmest month was August with an average temperature of 24.5°C and the warmest period of the growing season occurred during week 16 (27 July–2 August 2015) with an average temperature of 25.8°C.

Rainfall in June, August and September was higher than normal, whereas April, May, July and October had less precipitation than climate norms. September was the wettest month with a total rainfall of 153.6 mm and the wettest period was recorded during week 25, which experienced 102.4 mm of rainfall. Total precipitation during the study was recorded as 442.5 mm, which was close to historical precipitation records in Bahcekoy, Sariyer region recorded between 1974 and 2004. However, precipitation recorded during the study period was 112.5 mm higher than Istanbul climate norms. The longest dry period during the study lasted 21 days from 12 July to 1 August 2015. This dry period was followed by another 19 days without rain between 3 and 22 August 2015. Those periods were interrupted by a rainy day (2 August 2015) with a total precipitation of 10.4 mm. The coldest month of the study was April with an average temperature of 12.1°C and the coldest period was observed at week 2 between 20 and 26 April 2015 with an average temperature of 9.76°C (Figure 2).

3.2 Substrate physical and chemical properties

Particle size distribution of brick based commercial substrate were within the limits of the range recommended by German FLL Guidelines for green roof substrates (FLL, 2008). However nearly half of the mass consisted of particles from the 4 and 6 mm sieves. Particle size distribution of the pumice based substrate fell to the right curve limits of the range recommended by FLL guidelines, which can be interpreted as a coarser substrate that contained greater particles with 63.5% of the particles accumulated on the sieves 6 and 10 mm (Figure 1).

In terms of maximum water holding capacity (WHC), the brick based substrate met FLL Guidelines whereas the pumice based substrate was greater than recommended by FLL. Nitrogen and organic carbon levels of the substrates were between the thresholds recommended by FLL where those values were greater in brick-based substrate, which is closely correlated with soil organic matter (Powlson et al., 2013) and higher cation exchange capacity (CEC) (Caravaca and Albaladejo, 1999). In addition, infiltration rate of the coarser substrate (pumice-based substrate) was higher than the brick based substrate as expected, where all the substrates met the FLL requirements.

3.3 Plant growth

Between 28 April 2015 and 14 October 2015, 6 points in time (weeks 3, 6, 9, 15, 21 and 24) were chosen along with initial values to evaluate plant growth in the different substrates. Due to natural growth patterns prior to planting and dimensions of the seedlings, some differences were observed among plant species at the beginning of the study. In general, *S. album* and *S. acre* steadily increased in size during the study period regardless of substrate type. In contrast, growth of *Armeria* and *Achillea* plants were variable depending on substrate type and environmental conditions.

By week 6, significant differences in growth began to appear among treatments. At this point in time, *Armeria maritima* achieved the greatest PGI when grown in the (P7), (B7), and (B10) treatments. *Achillea millefolium* did best in the (P10) and (B10) substrates. The (P4), (B4), and (B7) treatments resulted in the least growth (Table 2, Figure 3). Among the *Sedum* species, *S. acre* exhibited the greatest growth in (B10), whereas the highest PGI for *S. album* was observed in the (P10) and (P7) treatments. The relatively low amount of precipitation that occurred during weeks 4 and 5 would favor the deeper substrate depths, especially for the herbaceous perennials.

The plant growth index of some plant species/substrate/depth treatments decreased through mid-June, (week 9), especially for *S. acre*. PGI values for *S. acre* decreased for all treatments except for (P10), whereas only the (B4) treatment resulted in a lower PGI for *S. album*. Environmental conditions affected the plants and growth of in deeper substrates were higher. PGI values for *A. maritima* decreased for all treatments except (P10) which also decreased, but not significantly. Statistically, there was no change in plants of *A. millefolium* between weeks 6 and 9. Comparing substrate types at week 9, *A. millefolium* and *S. acre* exhibited the greatest PGI in the (P10) and (B10) substrates. There were no differences observed among any of the substrate types for *S. acre*. However, there was a strong decrease on plant growth compared to previous weeks due to limited rainfall and moisture levels in the substrates.

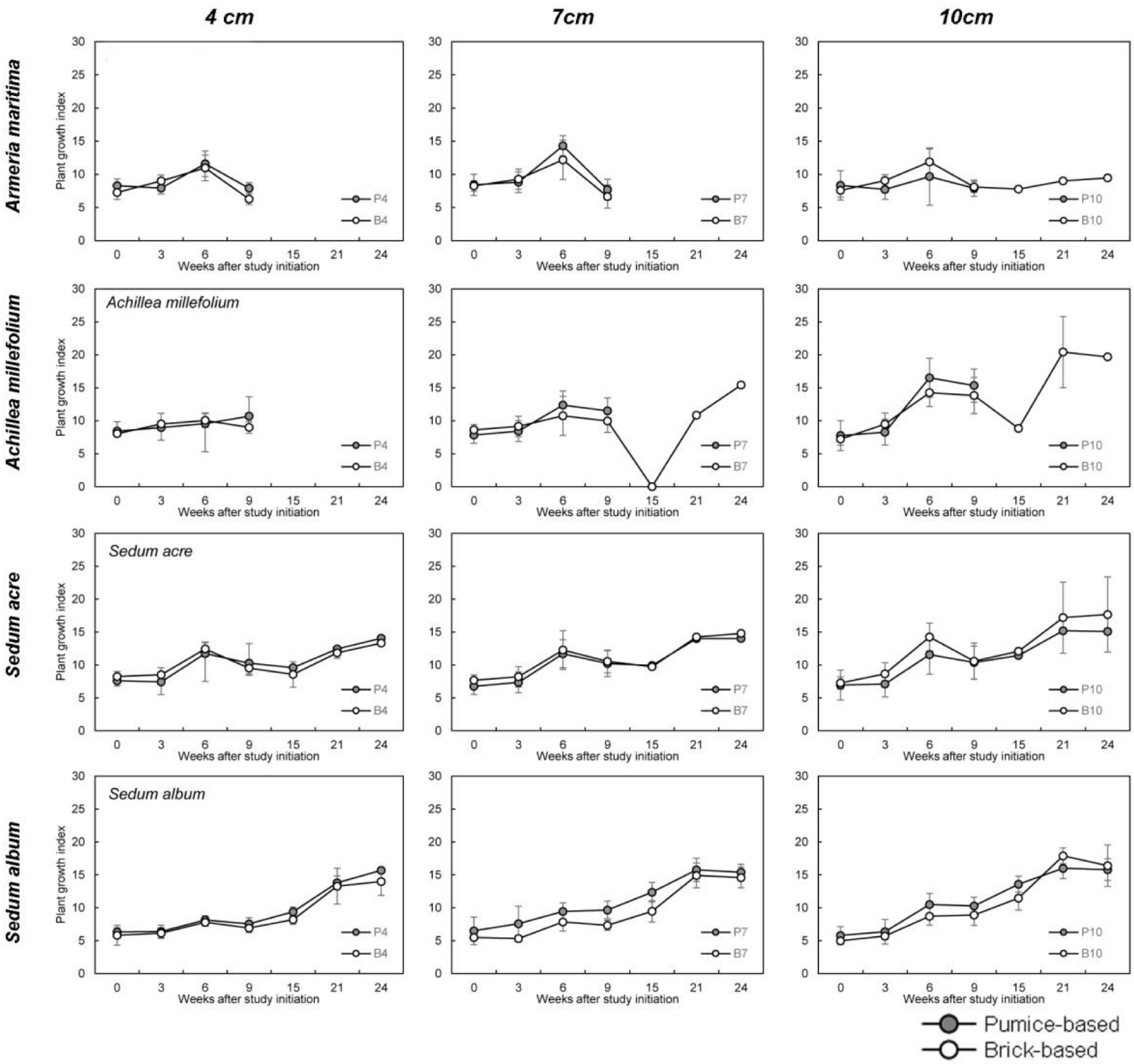
Week 15 was a breaking point for plant survival for the herbaceous perennials. The hottest and longest dry period of the study was recorded between 13 July and 1 August 2015 (weeks 14–16) which likely affected plant growth of the various treatments. Dry periods are typical in Mediterranean climates (Ceballos, et al., 2004) and is usually identified as the biggest challenge in green roof design due to water stress. This problem will likely become worse in the future due to climate change (Giorgi and Linello, 2008). *Armeria millefolium* and *A. maritima* were adversely affected by the drought period as only those plants growing in the (B10) treatments survived. In contrast, both *Sedum* species survived in all treatments. Moreover *S. album* exhibited significant growth during this period for all treatments except (B4). *Sedum album* showed consistent growth during the study and growth index continued to increase after week 15. The greatest growth for S. acre occurred in the deeper (P10) and (B10) substrates, whereas *S. album* had the highest PGI at (P7) and (P10). Overall, the deeper depths tended to outperform the shallower depths. This can be interpreted as shallow substrates not being suitable for those species during dry periods due to their low water retention abilities (Berndtsson, 2010; Getter and Rowe, 2009). There were no differences in PGI for *S. acre* between the two substrate types at the same depth, in contrast, *S. album* performed better when grown in (P7) and (P10) relative to (B7) and (B10). By week 21, (31 August–6 September 2015), rainfall that occurred after the long dry period positively influenced all plants regardless of substrate type or depth. This was especially true for *A. millefolium* where the plants growing in (B10) doubled in size. Surprisingly, new shoots were seen on *A. millefolium* plants that were reported as dead at week 15. However, those new shoots were only seen in (B7) and (B10) treatments and the remaining plants still appeared to be dead. Plants of *A. maritima* had died in all treatments after week 15 except for those in the (B10) treatment and this was continued until the end of the study. Those plants of *A. maritima* that did survive exhibited relatively slow growth for the remainder

TABLE 2. Mean absolute Plant Growth Index (PGI) over time of four plant species on two types of substrates in 4, 7, and 10 cm depths (P = pumice + municipal compost, B = crushed bricks + pumice + organic matter)

	P4	P7	P10	B4	B7	B10
Armeria maritima						
Week 0	8.27Ab	8.40Ab	8.33Aa	7.25Ac	8.25Abc	7.57Ab
Week 3	7.94ABb	8.81ABb	7.72Ba	9.01ABb	9.27Ab	9.05ABb
Week 6	11.59Ba	14.29Aa	9.66Ba	10.90Ba	12.18ABa	11.88ABa
Week 9	7.90ABb	7.70ABCb	7.89Aba	6.26Cc	6.64BCc	8.09Ab
Week 15						7.77Ab
Week 21						9.00Ab
Week 24						9.46Ab
Achillea millefolium						
Week 0	8.42ABb	7.83ABb	7.74ABb	8.03ABa	8.61Ac	7.22Bc
Week 3	8.98Aab	8.42Ab	8.27Ab	9.50Aa	9.14Abc	9.48Ac
Week 6	9.55Dab	12.37BCa	16.51Aa	10.03CDa	10.74CDb	14.25ABb
Week 9	10.68BCa	11.51Ba	15.33Aa	9.00Ca	9.98BCbc	13.83Ab
Week 15						8.83Ac
Week 21					10.83Abc	20.41Aa
Week 24					15.41Aa	19.7Aa
Sedum acre						
Week 0	7.59ABd	6.75Bd	6.94ABc	8.24Ad	7.66ABe	7.25ABf
Week 3	7.42ABCd	7.35BCd	7.09Cc	8.50ABcd	8.20ABCde	8.64Ae
Week 6	11.74Bb	11.70Bb	11.55Bb	12.44Bab	12.25Bb	14.25Ab
Week 9	10.27Ac	10.20Abc	10.37Ab	9.51Ac	10.53Ac	10.57Ad
Week 15	9.59BCc	9.92Bc	11.44Ab	8.55Ccd	9.74BCcd	12.07Ac
Week 21	12.44Cb	14.00Ba	15.20Ba	11.83Cb	14.25Ba	17.18Aa
Week 24	14.05BCa	14.01BCa	15.09Ba	13.31Ca	14.77BCa	17.66Aa
Sedum album						
Week 0	6.31Ae	6.50Ad	5.79ABd	5.81ABc	5.50ABd	4.98Bd
Week 3	6.38ABe	7.57Ad	6.35ABd	6.12Bc	5.31Bd	5.70Bd
Week 6	8.14Cd	9.44ABc	10.48Ac	7.77Cb	7.85Cc	8.70BCc
Week 9	7.55Cd	9.66ABc	10.27Ac	6.91Cbc	7.33Cc	8.90Bc
Week 15	9.38Cc	12.35ABb	13.59Ab	8.20Cb	9.46Cb	11.48Bb
Week 21	13.79Cb	15.75Ba	16.00Aba	13.27Ca	14.90BCa	17.88Aa
Week 24	15.68ABa	15.38ABa	15.79Aa	13.98Ba	14.59ABa	16.38Aa

Plant growth index (PGI) was calculated for each species at each substrate type by averaging the three individual growth measurements including plant height and two-dimensional width of seedlings. Week 0 = 29 Apr.2015; Week 3 = 120 May 2015; Week 6 = 12 Jun. 2015; Week 9 = 03 Jul. 2015; Week 15 = 13 Aug. 2015; Week 21 = 22 Sept. 2015; Week 24 = 14 Oct. 2015.
Mean separation in rows and columns by least significant difference ($P = 0.05$).
Uppercase letters in rows denote differences among substrates ($n = 9$).
Lowercase letters in columns denote comparisons over time within individual substrate types and species ($n = 6$).

FIGURE 3. Plant growth index (PGI) of plant species on various treatments (x-axis represents weeks after initiation and y-axis represents PGI values).



of the study, possibly because they had reached maturity. *Sedum acre* and *S. album* also exhibited much growth between weeks 15 and 21 with the greatest PGI recorded for (B10) for *S. acre* and (B10 and P10) for *S. album*.

By the final week of the study, PGI for *S. acre* was the greatest for those plants in the (B10) treatment, whereas the substrate depth did not make as much difference for *S. album* as only the (B4) treatment was significantly lower than the rest. Similar to previous weeks of the study, the least growth was usually observed at the shallow 4 cm depth. During the study period, all *A. maritima* except in the (B10) treatments failed to survive. PGI of *A. maritima* in (B10) was at its highest level at week 6. *Achillea millefolium* failed to survive in the pumice based substrates and 4 cm brick based substrates. PGI of *A. millefolium* was highest at the final week of the study in the (B7) and (B10) treatments. *Sedum* species reached their peak growth at the final week where all were alive. When comparing the two substrate types at the same depth, *S. acre* exhibited a greater PGI in the (B10) substrate relative to (P10). The (B4 compared to P4) and (B7 compared to P7) were not significantly different. The same comparisons for *S. album* showed that only the (B4) treatment resulted in a lower PGI.

According to Nagase and Dunnett (2010; 2012), *A. maritima* can adapt to thin substrate layers and can survive for three weeks with no water. However, our findings contradict those studies as substrates shallower than 10 cm failed to provide sufficient moisture for growth and survival during dry periods. This probably occurred because of climatic differences between experimental locations and longer dry periods in Istanbul compared to the U.K. However, our results demonstrate that *A. maritima* can be a good choice in green roofs if grown in at least 10 cm of a particular substrate in areas with a similar climate to Istanbul. *Armeria maritima* did not perform well in pumice-based substrate, which contains coarser particles. Thus, it is not recommended to plant *A. maritima* in porous substrate types. Similarly, *A. millefolium* was negatively influenced by dry periods. They only survived in the commercial (B) substrate and regardless of substrate type, this species did not survive at a depth of 4 cm. Furthermore, plants growing in the commercial substrate were still negatively affected from summer drought at the 7 cm depth. However, in the commercial substrate treatments, *A. millefolium* reproduced vegetative shoots by fall. Results demonstrate that plant species that depend on the C3 pathway such as *A. maritima* and *A. millefolium* failed to survive in substrate depths shallower than 7 cm. Drought tolerance of Sedum species were higher due to CAM photosynthesis.

Both *Sedum* species survived in all substrate depths and types. Although *S.acre* generally exhibited less growth in 4 and 7 cm deep substrates during dry periods, its growth rate increased by autumn with increased soil moisture and lower ambient temperatures. Still it did best in the 10 cm deep commercial substrate. All three depths were suitable for S. acre, but the deeper substrate provides a healthier growing environment.

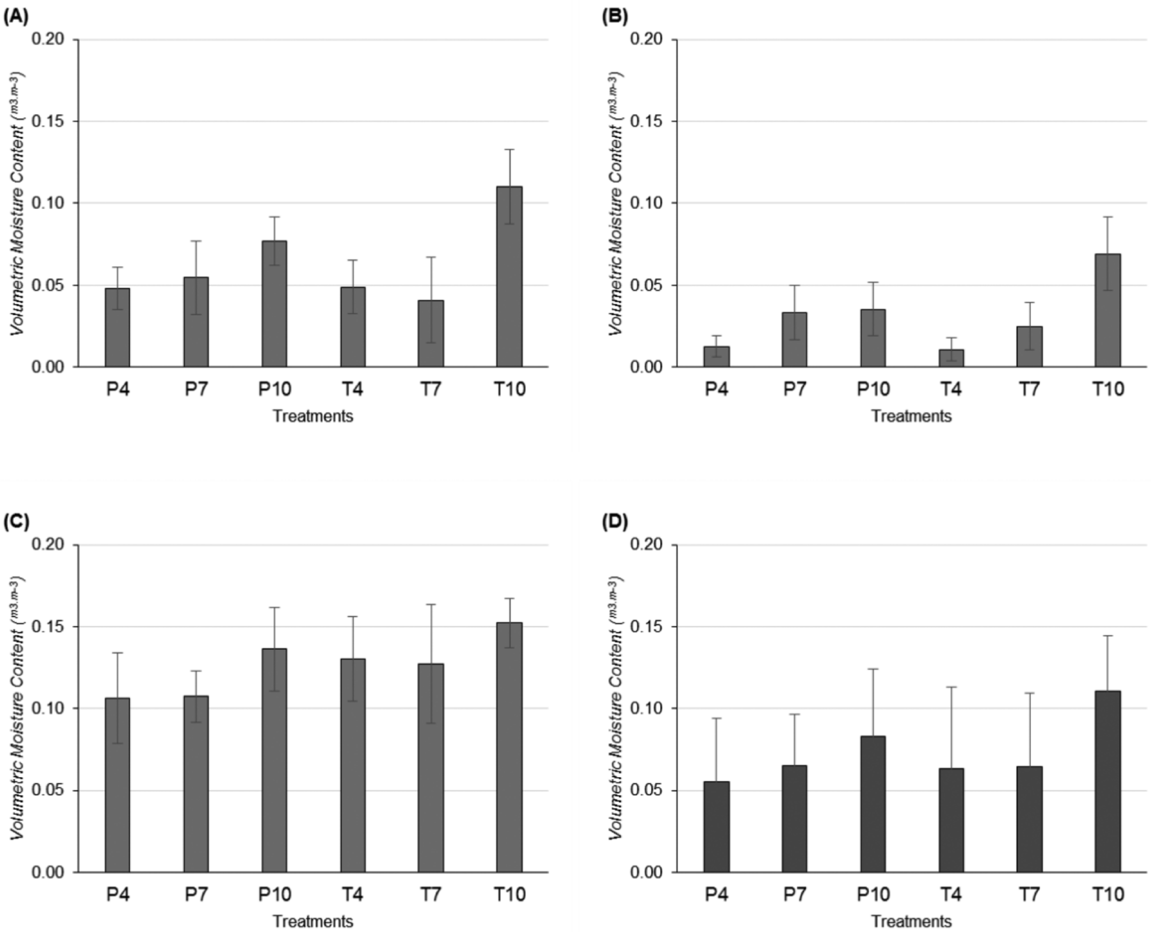
Sedum album exhibited favorable growth in all treatments. *Sedum album* would be a good choice in green roof applications throughout Istanbul and similar climatic areas and can be planted in a shallow or deep pumice based substrate and can survive in coarser substrate types. Results of our study corresponds to findings of Durhman et al. (2007) who reported that *S. album* can be good choice for green roofs when grown in various depths and subjected to dry periods. However, after planting they may require more time to obtain a sufficient roof surface coverage.

3.4 Substrate volumetric moisture content

Substrate volumetric moisture content (VMC) was affected by environmental conditions (rainfall, air temperature), substrate depth and type. On rainy days, substrate VMC in the various treatments was over 0.15. However, on hotter days without rainfall, sharp decreases were observed, especially following the 16-day dry period from 11 May 2015 until 20 May 2015, when the average ambient temperature was 18.4°C (Figure 4).

For both substrate types, VMC values were generally lower in the 4 cm substrate depths and greater in the deeper substrates. During drought periods, the shallower substrates dried out faster due to limited water availability in the substrates. This has been found to be true in other studies and shallower extensive green roof substrates experience wider fluctuations in temperature as well (Boivin et al., 2001; Eksi et al., 2017). However, in this study it should

FIGURE 4. Mean volumetric moisture content of the substrates in selected days. (A) 20.05.2015; 497 (B) 29.05.2015; (C) 08.06.2015 and (D) average moisture content of the treatments. (P) Pumice based substrate and (B) brick based substrate. Letters 4, 7 and 10 represents depth of the substrate treatments.



be pointed out that the crates were placed on benches and subject to air flow underneath the bench. Thus, they were exposed to different environmental conditions compared to media that is directly on the roof so the media is likely to dry out faster.

In the 4 cm treatments, substrate type did not strongly influence substrate VMC values. In the 7 cm deep treatments, VMC of the pumice-based substrate was slightly higher but not significant. In contrast, VMC of the 10 cm deep brick based substrate was 3.1% higher than the pumice based substrate. It is possible to confirm that porous structure, coarse particle size and air gaps in the substrate had a negative effect on water retention ability of the pumice-based substrate. Even though the pumice-based substrate exhibited a higher maximum water holding capacity in the laboratory tests (Table 1), this was not the case on the actual green roof microcosms. Apparently, its coarser structure and higher infiltration rate negatively influenced substrate moisture and plant growth. In contrast, the diverse particle size and silt-clay content in the brick based substrate positively influenced the water holding capacity. This especially supported relatively less drought tolerant plant species during hot and drought periods.

3.5 Shoot and root biomass accumulation

As stated by (Gregory, 2006) during water stress periods, root systems tend to grow more relative to shoots and thus root: shoot ratio increases. This was found to be true for the common green roof species *Sedum floriferum*, where the root: shoot ratio was highest for those plants subjected to the least amount of water (Rowe et al., 2014). With limited water availability in the root zone, *S. floriferum* partitioned greater growth to the root system relative to shoots. This could be explained considering the hydrotropic response of root systems (Takahashi, 1997). Although substrate VMC of (B10) treatment was still inadequate for optimal plant health, they still retained more moisture than the other substrates where the plants of *A. maritima* died. This was also confirmed by PGI findings in the study. The root: shoot ratio for *A. maritima* could only be detected in (B10) treatment and root growth was higher than shoot development.

In contrast, *A. millefolium* generated equal or higher root biomass and the root: shoot ratio was higher in the deeper (B10) substrate. However, they were not significantly different. As with *A. maritima*, the pumice based substrates failed to support *A. millefolium* during dry periods. Stirzaker et al. (1996) found that high porosity in a substrate could be more detrimental to plant growth than the supply of water and nutrients. Thus, high porosity of the pumice substrate in our study negatively influenced substrate moisture content and subsequent growth of both *A. maritima* and *A. millefolium* (Table 3).

Sedum acre generated the greatest biomass and had the lowest root: shoot ratio in the (B10) substrate (Table 3). Again, this makes sense as the shallower substrate treatments had limited substrate moisture. *Sedum album* responded similarly, however the results were not always significantly different.

CONCLUSIONS

Substrate type and depth influenced plant survival, growth, volumetric moisture content, and root: shoot ratios. The commercial substrate slightly outperformed the recycled substrate due primarily to its ability to hold more moisture, especially in the deeper treatments. Moisture content of the pumice-based substrate was greater in the laboratory setting, however, due to its coarser structure and higher infiltration rate, moisture content of commercial substrate was greater due to its finer particle size in the green roof microcosms.

During dry periods, *A. maritima* and *A. millefolium* might be suitable choices if supported by additional irrigation in substrates shallower than 10 cm. On the other hand, the native Sedum species from Istanbul and the surrounding Marmara region can easily be adapted to green roof systems. Even so, deeper substrates allow more options for plant selection along with greater plant growth, substrate moisture retention and plant survival during drought periods.

Although the recycled pumice did not perform as well as the commercial substrate, it still has potential. First, the recycled material would reduce the embodied energy of the roof thus reducing carbon emissions. Second, because it has a much lower bulk density, substrate depth could be increased without adding additional weight compared to the commercial substrate. In addition, it may be possible to process the recycled material to reduce particle size and in turn improve moisture retention.

There is a need for further research on substrates and native plant species to support proper green roof applications in Istanbul and similar climatic regions. Species and substrates examined within this study have not been previously reported for use on extensive green roofs in Istanbul.

TABLE 3. Shoot and root dry weight biomass accumulation (g) for Armeria maritima, Achillea millefolium, Sedum acre and Sedum album grown in two types of substrates and three substrate depths, (P4, P7, P10 = pumice + municipal compost at, 4, 7, and 10 cm depth; B4, B7, and B10 = crushed bricks + pumice + organic matter at, 4, 7, and 10 cm depth)

	Root	Shoot	Total	Root: shoot ratio
Armeria maritima				
P4	—	—	—	—
P7	—	—	—	—
P10	—	—	—	—
B4	—	—	—	—
B7	—	—	—	—
B10	6.88	5.19	12.07	1.33
Achillea millefolium				
P4	—	—	—	—
P7	—	—	—	—
P10	—	—	—	—
B4	—	—	—	—
B7	0.54 a	0.55 a	1.09 b	0.98 a
B10	2.60 a	1.64 a	4.24 a	1.59 a
Sedum acre				
P4	2.30 b	3.29 c	5.59 d	0.70 abc
P7	3.82 ab	5.53 b	9.34 bc	0.69 abc
P10	3.57 ab	7.22 a	10.78 b	0.49 bc
B4	2.25 b	2.28 d	4.52 d	0.99 a
B7	2.92 ab	3.92 c	6.84 cd	0.75 ab
B10	4.29 a	9.56 a	13.86 a	0.45 c
Sedum album				
P4	3.68 ab	4.07 b	7.75 b	0.90 a
P7	4.68 ab	6.05 a	10.73 ab	0.77 a
P10	7.45 a	7.38 a	14.83 a	1.01a
B4	3.07 b	3.43 b	6.49 b	0.89 a
B7	4.53 ab	4.31 b	8.84 b	1.05 a
B10	7.20 a	6.69 a	13.89 a	1.08 a

Initial dry weights (g) at time of planting for *A. maritima* (root = 8.41. shoot = 14.79. total = 23.2); *A. millefolium* (root = 32.49. shoot = 2.14. and total = 34.62); *S. acre* (root = 2.87. shoot = 5.82. and total = 8.69); *S. album* (root = 3.47. shoot = 1.83. and total = 5.30). Accumulation = Final dry weight – Initial dry weight. Mean separation in columns by least significant difference (P = 0.05).

An aim of this study was to increase the knowledge on green roof plant and substrate selection in Istanbul and serve as a reference for future green roof regulations and policies in Turkey.

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