PONTIFICIA UNIVERSIDAD CATOLICA DE CHILE

ESCUELA DE INGENIERIA

PLANT AND SUBSTRATE PERFORMANCE ON DIFFERENT GREEN ROOF DESIGNS IN A SEMIARID CLIMATE

FERMIN RODOLFO REYES PIÑA

Thesis submitted to the Office of Research and Graduate Studies in partial fulfillment of the requirements for the Degree of Master of Science in Engineering

Advisor:

CARLOS BONILLA MELÉNDEZ

Santiago de Chile, September, 2015

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To my Family and Verónica for their unconditional support.

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RESUMEN

Las cubiertas vegetales actuales han sido construidas y estudiadas principalmente en climas húmedos, donde se han identificado beneficios desde la aislación térmica hasta el aumento de biodiversidad. Sin embargo, poco se conoce de su desempeño en regiones áridas y semiáridas donde los requerimientos de irrigación pueden afectar la sustentabilidad de esta tecnología. Con el objeto de investigar y evaluar el desempeño de cubiertas vegetales en un clima semiárido, once módulos de cubiertas vegetales de 4 m^2 fueron monitoreados durante el primer año de establecimiento. El estudio se realizó en Santiago, Chile (33°26'S, 70°39'W, 570 MSNM), en una región con clima semiárido típico. Se evaluaron tres profundidades de sustratos (5 cm, 10 cm y 20 cm) y cuatro sistemas de drenaje disponibles en el mercado. Los módulos fueron implementados con un sistema de irrigación por aspersión e instrumentados para medir condiciones micro-climáticas de temperatura del aire, precipitación, velocidad del viento y humedad relativa, y humedad y temperatura del sustrato a intervalos de 5 min. Los resultados de las mediciones muestran que el espesor de sustrato controla la amplitud de la temperatura diaria de éste. Los diseños de 10 cm y 20 cm de profundidad mostraron un efecto de amortiguación significativo en la temperatura del sustrato. Adicionalmente, los diseños de 10 cm y 20 cm de profundidad alcanzaron temperaturas máximas del sustrato de hasta 13°C menor que la temperatura máxima del aire. En contraste, los diseños de 5 cm de espesor aumentaron la amplitud de la temperatura en los sustratos, alcanzando en promedio 13,8°C más que la máxima temperatura diaria en primavera, y 2,6°C menor que la temperatura mínima diaria en verano. Los módulos de 10 cm y 20 cm de profundidad mantuvieron niveles adecuados y estables de humedad en el sustrato durante todo el período de estudio. En tanto las cubiertas de 5 cm fueron las más afectadas por la demanda hídrica atmosférica. Aunque sus limitaciones fueron parcialmente superadas con el incremento de la irrigación o con la incorporación de telas o espumas retenedoras para aumentar la humedad del sustrato, las cubiertas de 5 cm experimentaron amplitudes térmicas diarias mayores a las recomendadas para el desarrollo de plantas. En consecuencia, las cubiertas extensivas de menos de 10 cm de espesor de sustrato no resultan adecuadas para climas áridos o semiáridos como el existente en este experimento, aun cuando en este estudio más del 77% de las especies de *Sedum* sobrevivieron después del séptimo mes incluida la temporada seca. Sin embargo, las altas tasas de irrigación para mantener las plantas vivas pueden ser consideradas una limitación en lugares donde el agua es escasa.

Palabras clave: Clima semiárido; disponibilidad de agua; *Sedum*; sobrevivencia de plantas; sustentabilidad urbana, techos verdes; temperatura del sustrato.

ABSTRACT

Green roofs have been built and studied mainly in humid climates providing many benefits from thermal insulation to biodiversity. However, little is known about their performance in arid and semiarid regions where the irrigation requirements can affects their sustainability. In order to investigate and evaluate green roofs performance in a semiarid climate, eleven 4-m^2 green roofs modules were built and monitored during the first year of establishment. The study was performed in Santiago, Chile (33°26'S, 70°39'W, 570 MASL), a region with a typical semiarid climate. Three substrate depths (5-cm, 10-cm and 20-cm) and four commercial drainage systems were evaluated. The modules were implemented with a sprinkler irrigation system and instrumented to record air temperature, precipitation, and substrate water content and temperature at 5-min intervals. The results showed that substrate depth controls the amplitude in substrate temperature. The 10-cm and 20-cm depth designs showed a significant dumping effect in substrate temperature. In addition, the 10-cm and 20-cm depth designs showed maximum daily temperatures up to 13°C below the air temperature. In contrast, the 5-cm depth designs increases the amplitude in substrate temperature, reaching in average 13.8°C more than the daily maximum air temperature in spring and 2.6°C less than the daily minimum air temperature in summer. On the other hand, the 10-cm and 20-cm depth modules provided a stable and suitable substrate water content along the entire study period, but the 5-cm depth green roofs were more affected by the atmospheric demand. Even though their limitations were partially overcome by increasing irrigation rates or adding a retention fabric to improve the substrate water holding capacity, the 5-cm depth green roofs experienced daily thermal amplitudes beyond the recommended value for plant development. Consequently, extensive (or thin) green roof (less than 10 cm of growing medium) are unlikely to be recommended in arid or semiarid climates, even though in this study more than 77% of the *Sedum* species survived after seven month which includes the dry season. However the high irrigation rates to keep them alive could be a limitation in areas where the water scarce.

Keywords: Green roofs; plant survival; *Sedum* ; semiarid climate; substrate temperature; urban sustainability; water requirements.

1. INTRODUCTION

One of the main challenges for sustainable urban development is climate change. In developing country such as Chile, the urban expansion and the absence of sustainable urban planning have led to alterations of the earth's surface and consequent negative impact on several ecological processes and regional climates (Grimm et al., 2008). Urbanization implies changes in land use and cover, promoting impermeable surfaces at the expense of pre-existing bare soil or vegetation. Furthermore, urban development has dramatically increased greenhouse gas emissions, including carbon dioxide, and the use of fossil fuels has led to air quality problems too. These problems and the use of materials with low albedo such as asphalt, increases other environmental issues such as flooding and urban heat island effects in cities (Carter, 2011).

Urban green spaces are effective solutions to improve the health of urban population, especially in large cities. Unfortunately, this kind of areas are reduced in Latin America due to the explosive urbanization processes occurred in the second half of the 20th century (Reyes and Figueroa, 2010). The Santiago city Metropolitan Area (Chile) is an example of these issues. Indeed, even though in the last decades significant investments in building and reclamation of green spaces have been made, large differences still remains in the green spaces distribution among the towns in the city (De la Maza et al., 2002; Escobedo et al., 2006; Figueroa, 2009). According to the OECD 2013 report, only the cities of Temuco and Punta Arenas have at least the minimum number of green space square meters recommended per person. While the recommendation is 9 m^2 per person, Santiago only has 3.46 m^2 per person.

Different types of green spaces and green infrastructure have been developed in urban areas. Razzaghmanesh et al. (2014), summarized some green spaces which has a positive effect on stormwater management such as the Low Impact Development (LID), Best Management Practice (BMP), Sustainable Urban Drainage Systems (SUDS), Low Impact Urban Design and Development (LIUDD) and Water Sensitive Urban Design (WSUD). On the other hand, green infrastructure includes areas such as the green roofs, green walls, bioretention systems, swales, parklands and permeable and porous pavements (Razzaghmanesh et al., 2014).

Typically 20–40% of the impervious area in an urban environment is occupied by conventional roofs (Carter and Jackson, 2007; Kingsbury and Dunnett, 2008). Along with the streets, the roofs are the first surface that receives precipitation, and shows the potential of green roofs in an urban environment to be one of the most important types of green infrastructure for source control rainfall. Green roofs are typically flat and slightly sloped surfaces designed to support vegetation growth thanks to a drainage layer, a lightweight media and a hardy plant palette. Many environmental benefits have been reported for this technology such as improvement of thermal and acoustic insulation, stormwater control by reduction and delay of precipitation runoff, increase and improvement of urban biodiversity, and mitigation of the urban heat island effect through cooling due to evapotranspiration (Berardi et al., 2014).

Green roofs were first constructed in Germany and Scandinavia. Since two decades ago green roofs have been widely studied in the United States. Now there are guidelines in Europe and USA for designing and choosing appropriate vegetation for green roofs in temperate, humid, and rainy regions. Projects have sparsely been developed in dry and hot regions, such as Mediterranean and semi-arid/arid zones (Nektarios et al., 2011; Issa et al., 2015). Because the research in these areas is limited, green roofs are currently constructed according to the experience in humid and rainy regions. However, the difference in rainfall amount, humidity and temperature compared to the typical condition in arid zones affects the green roof energy and water balances and leads to failures when designing and building with those standards in dryer areas (Williams et al., 2010).

As green roofs are man-made ecosystems, regional differences in climate, rooftop microclimate, and plant needs must be considered in the design of green roofs to get their benefits. Thus, the timing for building, planting method, and irrigation management must be taken into account, especially throughout the establishment period. This is crucial to increase the chances of success when building a green roof in a semiarid region.

2. LITERATURE REVIEW

2.1. Green roof structure and classification

Green or living roofs are typically flat and slightly sloped surfaces designed to support the vegetation growth (Dvorak and Volder, 2010). Green roof structure consists of different layers: a water proofing membrane over the rooftop, a drainage or retainer system, an anti-root membrane, and a filter membrane (if needed) to place under and over drainage respectively, a substrate layer, and plants (Oberndorfer et al., 2007; Berndtsson, 2010). Substrate type and depth plays an important role in green roofs (Thuring et al, 2010). Substrate is a specific and engineered growth media that is lighter than topsoil, better drained, primarily inorganic, and capable of supporting plant growth (Morgan et al., 2012). Substrate depth can range from few centimeters to even a meter.

There are two general types of green roofs: extensive and intensive. Extensive green roofs, also referred as eco-roofs or light weight green roof, have a substrate layer from 2 to 20 cm depth, require minimal or no irrigation, and are usually planted with moss, succulents, grass, and some herbaceous plants (Dunnett and Kingsbury, 2004; Oberndorfer et al., 2007). Intensive green roofs are deeper than 20 cm, often designed as gardens for human use, and usually require irrigation and maintenance. They also can support wild shrubs, coppices, small trees, and lawn (Oberndorfer et al., 2007; FLL, 2008).

2.2. Green roofs history and reported benefits

The first green roof research was developed to mitigate the damaging physical effects of solar radiation on the roof structure (Köhler, 2006; Mentens et al., 2006; Oberndorfer et al., 2007) and also employed as fire retardant structures (Köhler, 2003). In the last two decades there has been substantial expansion of extensive green roof research in humid and temperate climates of Western and Central Europe, North America, Japan, and

China, where some ecological, economic, and social benefits provided by green roofs at a variety of scales have been reported. Some of these benefits relate to the increment in roof life and improvement of thermal and acoustic insulation of individual buildings (Kosareo and Ries, 2007; Van Renterghem and Bottledooren, 2008; Jim and Tsang, 2011; Jaffal et al., 2012), storm water management by reduction and delay of precipitation runoff (VanWoert et al., 2005; Fioretti et al., 2010), increment and improvement of urban biodiversity (MacIvor and Lundholm, 2011), mitigation of the so called urban heat island effect through cooling due to evapotranspiration (Alexandri and Jones, 2008), improvement of air and water quality (Yang et al., 2008; Gregoire and Clausen, 2011) and a psychological benefit for humans because green roofs make a more healthy and esthetically pleasing environment in which to work and live (Oberndorfer et al., 2007).

2.3. Green roofs in temperate, arid and semiarid regions

In temperate regions rainfall is usually equally distributed through the year, a condition that promotes growth of vegetation. In recent years the green roof industry has experienced a significant expansion in these regions (Oberndorfer et al., 2007). However, development of green roof projects has been limited in dry and hot regions, such as Mediterranean and semi-arid/arid zones (Nektarios et al., 2011; Issa et al., 2015). Because research in these zones is limited, green roofs are currently constructed based on standards developed in temperate regions. However, the differences in precipitation, humidity and temperature, and thus the energy and water balances, between these areas are considerable. Therefore, the lack of a proper design could lead to severe project failures (Williams et al., 2010). Indeed, in dry and hot regions, maintaining the plant community through the dry season without using a large amount of irrigation water becomes challenging.

The difference in climate affects other design objectives. For example, in temperate regions, a green roof will be expected to insulate the building in both winter and summer and manage storm water runoff. In dry and hot areas, controlling the heat transfers during the dry spring and summer will be the first priority. In addition to design requirements, in Europe and more recently in the USA, hundreds of plant species have been identified for use on green roofs (Monterusso, Rowe and Rugh, 2005; Getter and Rowe, 2006; Durhman, Rowe and Rugh, 2007; Cantor, 2008). As green roof technology continues developing in dry regions, more information about the performance and adaptation of these plant species is needed (Dvorak and Volder, 2013).

Plant establishment is a critical period for a green roof project, and plant development and surface coverage could be especially limited in arid and semiarid climates. In order to promote plant growth in semiarid climates irrigation is required. However, a suitable design should avoid irrigation after plant establishment (Dunett and Kingsbury, 2004; Getter and Rowe, 2006). In arid and semiarid climates this recommendation challenges the roof survival, and a proper irrigation system and management are crucial.

2.4. Objective

This thesis investigates the plant and substrate performance of nine 5, 10 and 20-cm depth green roof modules with different layering and evaluates the effect of the water retention layer on substrate volumetric water content and temperature. The following variables were monitored at 5 min basis: (a) substrate temperature and volumetric water content in the substrate of the nine green roof designs, (b) on-site weather conditions of air temperature, relative humidity, wind speed and solar radiation. Finally, two plant survival survey were carried out one and seven months after planting.

3. MATERIALS AND METHODS

3.1. Study site

The study was developed in the green roof infrastructure laboratory (LIVE for its acronym in Spanish, Figure 3-1) at the Pontificia Universidad Católica de Chile, in the city of Santiago (33°26’S, 70°39’W, 570 MASL). Santiago has a cold steppe or semiarid climate according to the Köppen-Geiger climate classification (Kottek et al., 2006), with an aridity index (ratio between average annual precipitation and average annual reference potential evapotranspiration) of 0.36 (Uribe et al., 2012). It is characterized by hot and dry springs and summers and mild and wet winters. The mean annual rainfall is approximately 310 mm, which occurs mainly between May and August (Bonilla and Vidal, 2011). In summer, the average maximum temperature is 30°C (data from Dirección Meteorológica de Chile, weather station of Quinta Normal, Santiago).

3.2. Instrumentation used

To characterize the microclimates demands for the plants, a weather station was installed in the LIVE (Figure 3-2). The station had a series of high-resolution sensors for recording temperature and relative air humidity (EHT, Decagon Devices), wind speed and direction (Davis Cup, Decagon Devices), precipitation (ECRN-100, Decagon Devices) and net solar radiation (SP Lite2, Kipp & Zonen). In addition, volumetric soil water content (VWC), soil temperature and electrical conductivity were recorded with a sensor installed on half the thickness of substrate (GS3, Decagon Devices). All sensors were connected to a recorder, which collected data every 5 minutes from November 2013 to November 2014.

3.3. Building infrastructure plant laboratory (LIVE)

LIVE consisted on a reinforced concrete construction of 2-m high with 11 4 m^2 green roofs designs or modules on the upper slab (Figure 3-1). Each green roof module had a combination of seven types of Sedums (*Sedum spurium*, *S. kamtschaticum*, *S. reflexum*, *S. sexangulare*, *S. album*, *S. hybridum* and *S. rupestre*) as shown in Figure 3-3, planted with a density of 49 plants m^{-2}. A commercial substrate was used in all the modules, with a sandy loam texture (68% sand, 20% silt, and 13% clay). The substrate was mainly inorganic with less than 3% of organic matter, pH 7.4 and 2.52 mS cm^{-1} of electrical conductivity. Using a pressure plate over three random substrate samples, we determined a water retention of 0.08 m^3m^{-3} of plant available water, computed as the difference between permanent wilting point (0.15 m^3 m^{-3}) and field capacity (0.23 m^3 m^{-3}).

Figure 3-1. Green roof installation at LIVE eight months after planting. The sprinkler irrigation system was located at the corner of each green roof module. The 20-cm substrate depth green roof fully covered by vegetation is shown at the bottom left of the picture.

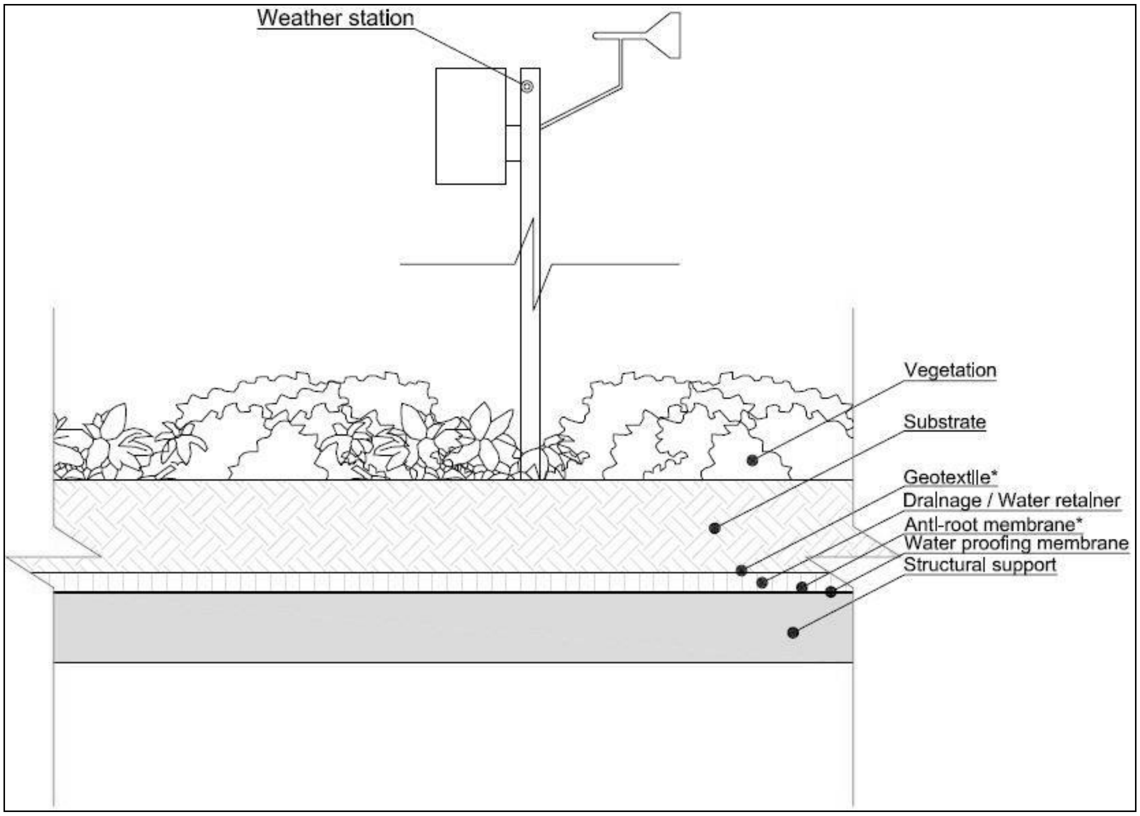

Figure 3-2. Cross-section of the green roof design, including the on-site weather station two meters above green roof surface and the typical substrate and layers. The occurrence of some layers (*) depends on the type of drainage or retention system.

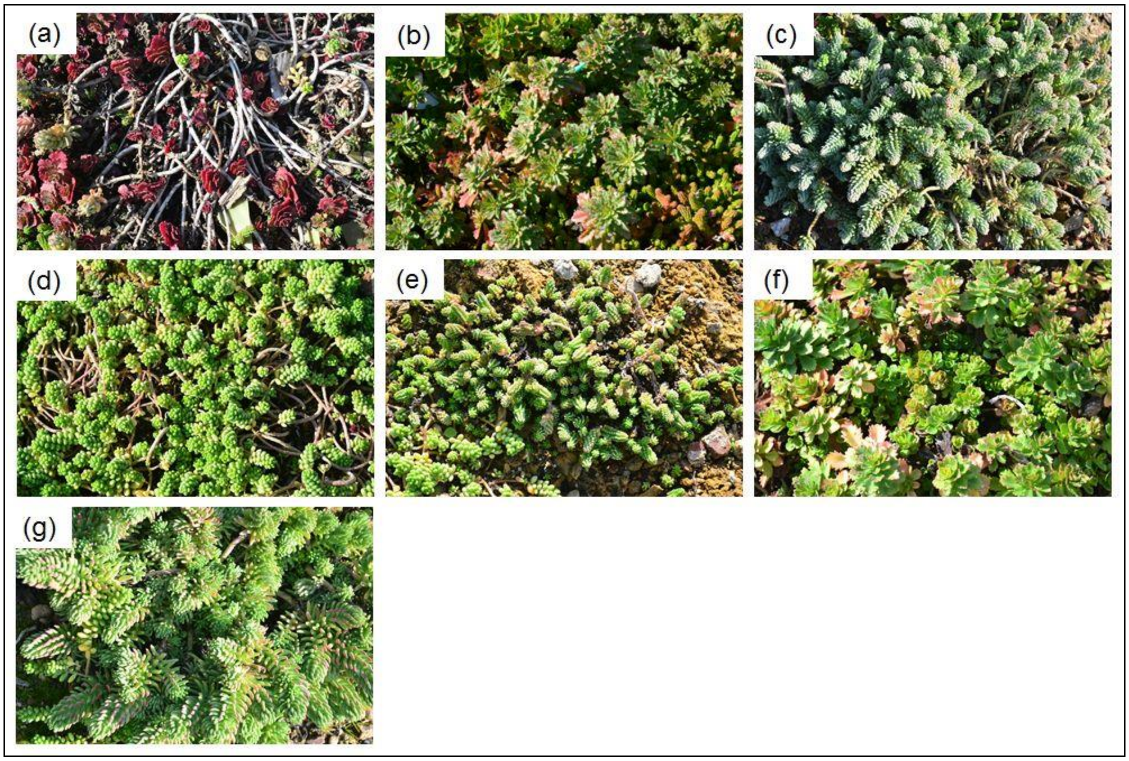

Figure 3-3. *Sedum* species used in each green roof module. *Sedum spurium* (a), *S. kamtschaticum* (b), *S. reflexum* (c), *S. sexangulare* (d), *S. album* (e), *S. hybridum* (f) and *S. rupestre* (g). Plants can be differentiated because pictures were taken in autumn when no water or temperature stress occurs. However, when the harsh condition were evident, *S. reflexum* resembles *S. rupestre*, and *S. kamtschaticum* resembles *S. hybridum*.

3.4. Experimental design

Among the 11 green roofs modules, three substrates depths were evaluated (5, 10, and 20 cm); three commercial drainage or retention systems were tested for the 5-cm depth modules, four for the 10-cm depth modules and one for the 20-cm depth module (Table 3-1 and Figure 3-2). Moreover, one 10-cm depth module with no drainage or retention system was also considered. The results shown for module 7 are the average of three replicates that were used to evaluate the natural variability of measurements within the laboratory.

Two drainage system were evaluated. Both systems consisted of a geotextile layer, a drainage layer and an anti-root layer (Figure 3-2 and Figure 3-4), the drain pipe was 1 inch in diameter installed in an edge of the green roof. One drainage system had a drain capacity (DC) between dimples of 63 L min^{-1} m^{-1} and was used in 5-cm and 10-cm depth modules. The other drainage system had a DC of 161 L min^{-1} m^{-1} and was used in 10-cm and 20-cm depth modules (Table 3-1). In addition, 5-cm and 10-cm depth modules were also used with two retainers (Table 3-1). One retainer had a water retention capacity (WRC) of 4 L m^{-2} and the other one had a 30 L m^{-2} WRC (Table 3-1 and Figure 3-4). In all modules, a sprinkling irrigation system was set up at the beginning of the study.

Table 3-1. Green roof designs based on substrate depth and water retention capacity or drain capacity of the retention or drainage system. Two retainers and one drainage system was tested in 5-cm depth modules. Two retainers, two drainage systems and one module with no retainer or drainage system were tested in 10-cm depth modules. Only one drainage system was tested in a 20-cm depth module.

Design module	Substrate depth (cm)	Drain capacity between dimples of the drainage system (L min^{-1} m^{-1})	Retainer water retention capacity (L m^{-2})
1	5	63	-
2	5	-	4
3	5	-	30
4	10	63	-
5	10	-	4
6	10	-	30
7	10	161	-
8	10	-	-
9	20	161	-

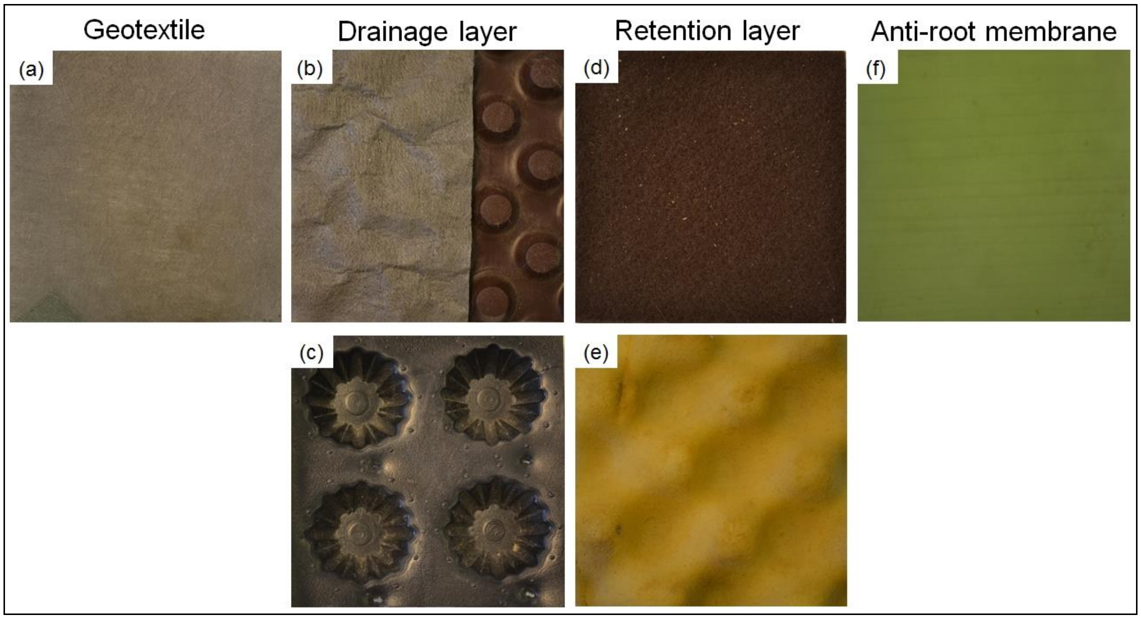

Figure 3-4. Components of the drainage and water retention systems used in green roof modules. Drainage system of 63 L min^{-1} m^{-1} drain capacity between dimples consisted on a geotextile (a), a drain (b) and an anti-root membrane (f); and the drainage system of 161 L min^{-1} m^{-1} drain capacity between dimples was composed of a geotextile (a), a drain (c) and an anti-root membrane (f). The retainer of 4 L m^{-2} of water retention capacity was (d) and the retainer of 30 L m^{-2} water retention capacity was (e). All pictures are at scale.

3.5. Plant survival and green roof surface coverage

Substrate and climate measurements began in November 2013, and green roof plantation finished in mid-September 2013. One and seven months after plantation (mid-October 2013 and mid-April 2014) the plant establishment was evaluated. The objective of the first evaluation was to identify plant survival in each green roof design and substrate depth. The second evaluation was to identify the plant survival to green roof harsh conditions in the spring-summer season. In each survey the number of each plant that was alive on each green roof design was counted.

Because of the high plants density, each type of *Sedum* was marked to facilitate the survey (Figure 3-5). However, two pairs of species (i.e. *S. kamtschaticum* and *S. hybridum,* and *S. reflexum* and *S. rupestre*) were difficult to differentiate. Thus, plants belonging to these two groups were counted together to avoid errors in the analysis.

Figure 3-5. Module 9 one month after planting. *Sedum* species are marked with little colored plastic tube to facilitate the identification of each species.

Planting design considered 196 plants, 28 plants of each type of sedum evenly distributed in every green roof module. Nevertheless, after first survey was done, little differences between the theoretical planting scheme and the real planting scheme were observed. However, the total number of plants per green roof module was still 196, and the number of each type of *Sedum spp.* per module varied from 23 to 33 species.

4. RESULTS AND DISCUSSION

4.1. Climate condition at the green roof

During the study period, the monthly average maximum air temperature exceeded 25°C between October and March. The maximum monthly average air temperature was 30.9°C in January, and the maximum daily temperature of 34.9°C was recorded on January 11, 2014. Between April and August, the average monthly minimum temperatures were below 10°C. The coldest month was June, with an average minimum temperature of 3.5°C, and the lowest daily temperature was -0.07°C, recorded in July (Figure 4-1a).

On 18 days during the study period, precipitation greater than 2 mm was recorded, with a total of 250 mm. Almost all the precipitation occurred between May and September, mainly distributed in 12 events. Other rainfall events of less than 2 mm had no effect on the green roof substrate water content, as the plant leaves intercepted all that water (Appendix 4). In dry months, water was supplied with the sprinkling irrigation system, adding a total of 6.2 m during the year (Figure 4-1b). Approximately 70% of this irrigation was provided between December 2013 and February 2014, as planting was in November under harsh atmospheric conditions. The atmospheric demand, computed as potential reference evapotranspiration using Penman-Monteith equation (Allen et al., 1998), reached its maximum in summer, then in spring, autumn and winter, with averages of 4.5, 4.2, 1.4 y 1.2 mm d^{-1}, respectively. The aridity index during the year of study was 0.23, close to the minimum value for a semiarid climate that is 0.2. This semiarid situation, combined with the low relative humidity (monthly averages in spring and summer lower than 50%) and the lack of precipitation (Figure 4-1b), demonstrates how crucial the irrigation system is to provide suitable conditions for plants survival in semiarid and arid climates.

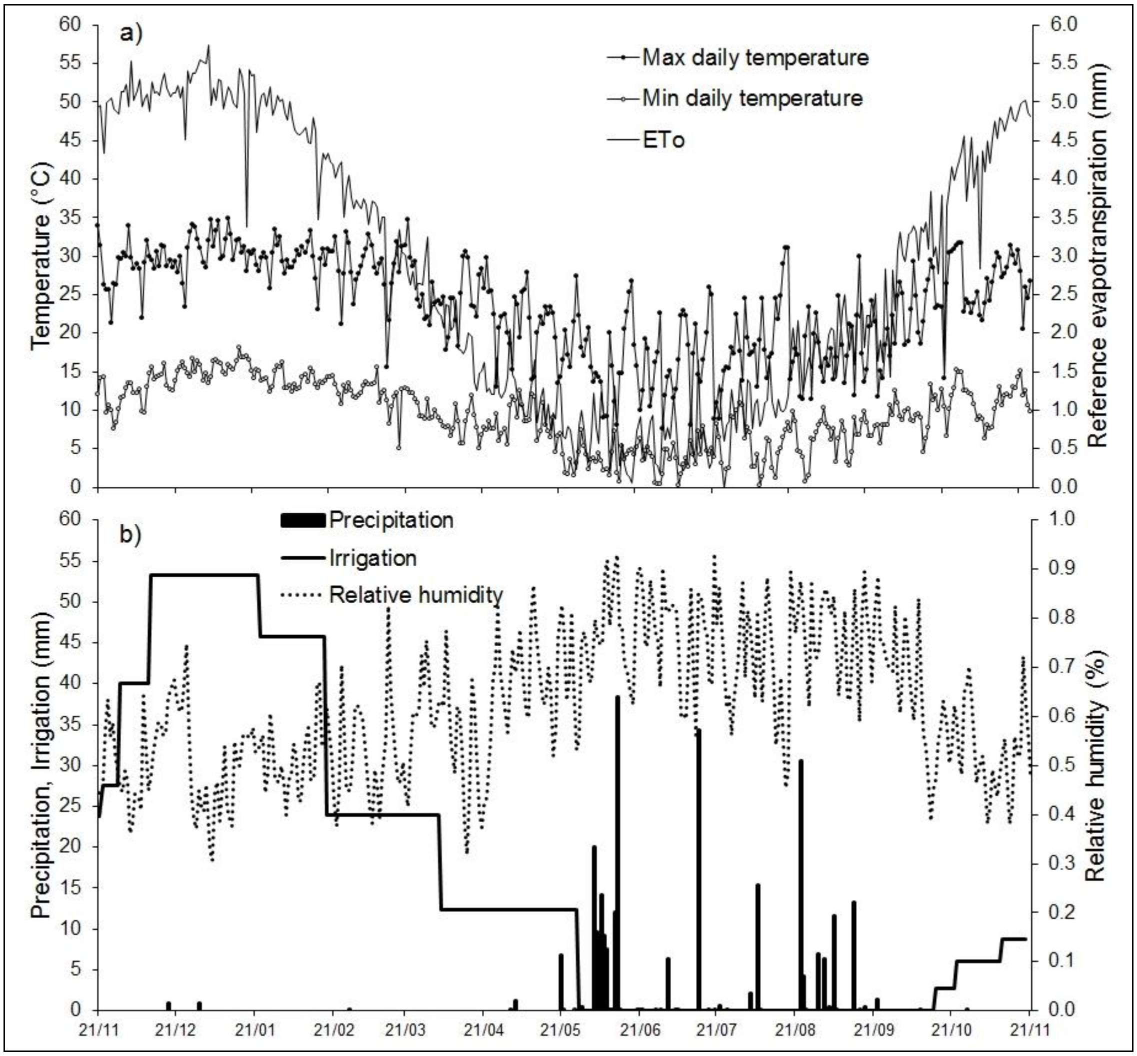

Figure 4-1. Atmospheric data collected at the green roof modules during the study period (November 21, 2013 to November 21, 2014). The figures show (a) minimum and maximum daily temperatures, and reference evapotranspiration, and (b) rainfall, irrigation and relative humidity.

To monitor climate condition, registered on-site data and typical online data for Santiago (from La Platina, a weather station located 8 km south of LIVE) were compared. Air temperature, relative humidity and solar radiation data were correlated with a $R^2 > 0.95$

between the weather station and LIVE. However, on-site, the annual precipitation was 10% higher (24 mm) than online data, but this was not relevant as the differences occurred in autumn and winter, when irrigation was not needed because of low temperature and high relative humidity.

4.2. Substrate temperature

Small differences (≤ 2°C) were observed between mean air temperature and mean substrate temperature in all green roofs modules. As shown in Table 4-1 the differences were higher in the spring season in all green roofs modules because irrigation was activated at low rate at the beginning that season, and no irrigation was applied in winter (Figure 4-1b). Thus, the highest difference between mean air temperature and mean substrate temperature was 7.9°C, recorded in October 2014 in module 1.

Table 4-1. Seasonal mean temperature, mean thermal oscillation (difference between maximum and minimum daily temperature) and maximum temperatures in air and substrate in green roof modules. Substrate temperature was measured at half substrate depth.

		Green roof modules									
		1	2	3	4	5	6	7	8	9	Air
		Temperature °C									
Summer	Mean Temp.	22.1	21.0	21.1	22.0	20.8	22.2	22.1	21.2	20.7	22.5
	Mean Ther. Osc.	24.7	23.4	18.3	10.3	6.4	6.4	9.7	7.2	2.0	15.7
	Inst. Max. Temp.	48.3	45.7	41.0	35.3	29.3	29.9	39.2	29.6	25.2	34.9
Autumn	Mean Temp.	12.9	12.0	12.1	12.8	12.1	13.2	12.8	11.6	12.9	13.3
	Mean Ther. Osc.	16.0	15.0	9.5	5.2	3.4	4.3	5.5	4.6	1.5	14.2
	Inst. Max. Temp.	34.6	31.6	26.7	24.7	21.7	24.3	25.8	23.1	19.2	34.7
Winter	Mean Temp.	11.2	10.6	11.0	11.7	11.6	12.3	11.9	12.5	12.5	10.6
	Mean Ther. Osc.	13.7	13.8	9.1	4.5	3.1	3.9	4.6	4.1	1.5	12.3
	Inst. Max. Temp.	31.2	29.3	25.4	23.1	22.1	23.2	24.0	24.3	20.5	31.0
Spring	Mean Temp.	22.7	21.4	21.5	23.5	22.0	23.0	23.3	23.0	22.5	18.2
	Mean Ther. Osc.	30.3	31.0	26.8	13.4	9.3	9.7	12.3	8.7	4.0	15.0
	Inst. Max. Temp.	54.0	53.0	53.5	38.4	34.5	33.3	38.8	34.5	29.6	34.0

Mean substrate thermal oscillation (TO_s) was inversely proportional to substrate depth in modules with equal drainage or retention system. Figure 4-2 and Table 4-1 show that minimum and maximum daily temperatures were more extreme in 5-cm depth green roof than in 10-cm depth modules. The 5-cm depth modules reached higher maximum substrate temperatures than 10-cm depth modules, and also lower minimum substrate temperatures than 10-cm depth modules. Modules 1, 2 and 3 had mean TO_s up to 21°C higher than that for modules 4, 5 and 6 which had equal drainage or retention system but different substrate depth respectively (Table 4-1). It is important to mention that October 2014 was the month with the highest daily TO_s with a maximum value of 45.8°C registered on October 11, 2014 in module 1. That day the maximum substrate temperature reached 54°C. Similarly, module 7 had mean TO_s up to 8.3°C higher than mean TO_s in module 9. However in this case maximum substrate temperature were lower than 40°C and therefore, plant survival was not at risk.

When the mean air thermal oscillations (TO_a) were compared with the mean TO_s of the green roof modules, 20-cm and 10-cm depth modules showed a dumping effect over the air temperature. Substrate temperature in module 9 was 10°C to 13°C below the maximum air temperature, and in 10-cm depth modules the substrate temperature was 2°C to 9°C below the maximum air temperature. These results agree with those from Nardini et al. (2012), who showed that 12-cm and 20-cm depth green roofs have a dumping effect over air temperature in summer. However, 5-cm depth modules amplified the TO_a, which reached a mean value up to 15.3°C higher than the mean TO_a in spring (Table 4-1). Additionally, the 5-cm depth modules reached a maximum TO_s 29°C higher than TO_a, which resulted in a substrate temperature up to 26°C higher than maximum air temperature.

The impact of altering substrate water retention properties over TO_s in 5-cm depth green roofs is shown in Figure 4-2a, Figure 4-2b and Figure 4-2c. Mean TO_s observed in modules 1 and 2 were nearly the same, with mean TO_s differences not exceeding 1.5°C during the study period. In fact, the TO_s in spring in module 2 exceeded the value observed in module 1 by 0.7°C on average (Table 4-1). In other words, the use of a 63 L min^{-1} m^{-1} DC drainage system and 4 L m^{-2} WRC retainer had the same effect on TO_s in 5-cm depth green roof modules. The use of a 30 L m^{-2} WRC (module 3) reduced the TO_a by 6°C during summer and 3°C in spring (Table 4-1). Unfortunately for plant survival, module 3 still reached a high maximum substrate temperature of 53°C in October 2014, when the substrate water content was below 0.1 m^3 m^{-3}.

Figure 4-2 d-h show the effect of the five modules over TOs on 10-cm depth green roofs. There were no significant differences in mean temperature during the study period. The mean TO_s and instant maximum substrate temperature during summer and spring are compared in (Table 4-1). Modules 5, 6 and 8 (the modules with a 4 L m^{-2} WRC retainer, a 30 L m^{-2} WRC retainer and the module without drainage or retention system, respectively) reduced the mean TO_s by approximately 3.5°C compared with that associated with modules 4 and 7, which had drainage systems of 63 and 161 L min^{-1} m^{-1} DC, respectively. In addition, while modules 5, 6 and 8 reached maximum temperatures of 30°C in summer and 34°C in spring, modules 4 and 7 reached maximum temperatures of 37°C in summer and 38°C in spring.

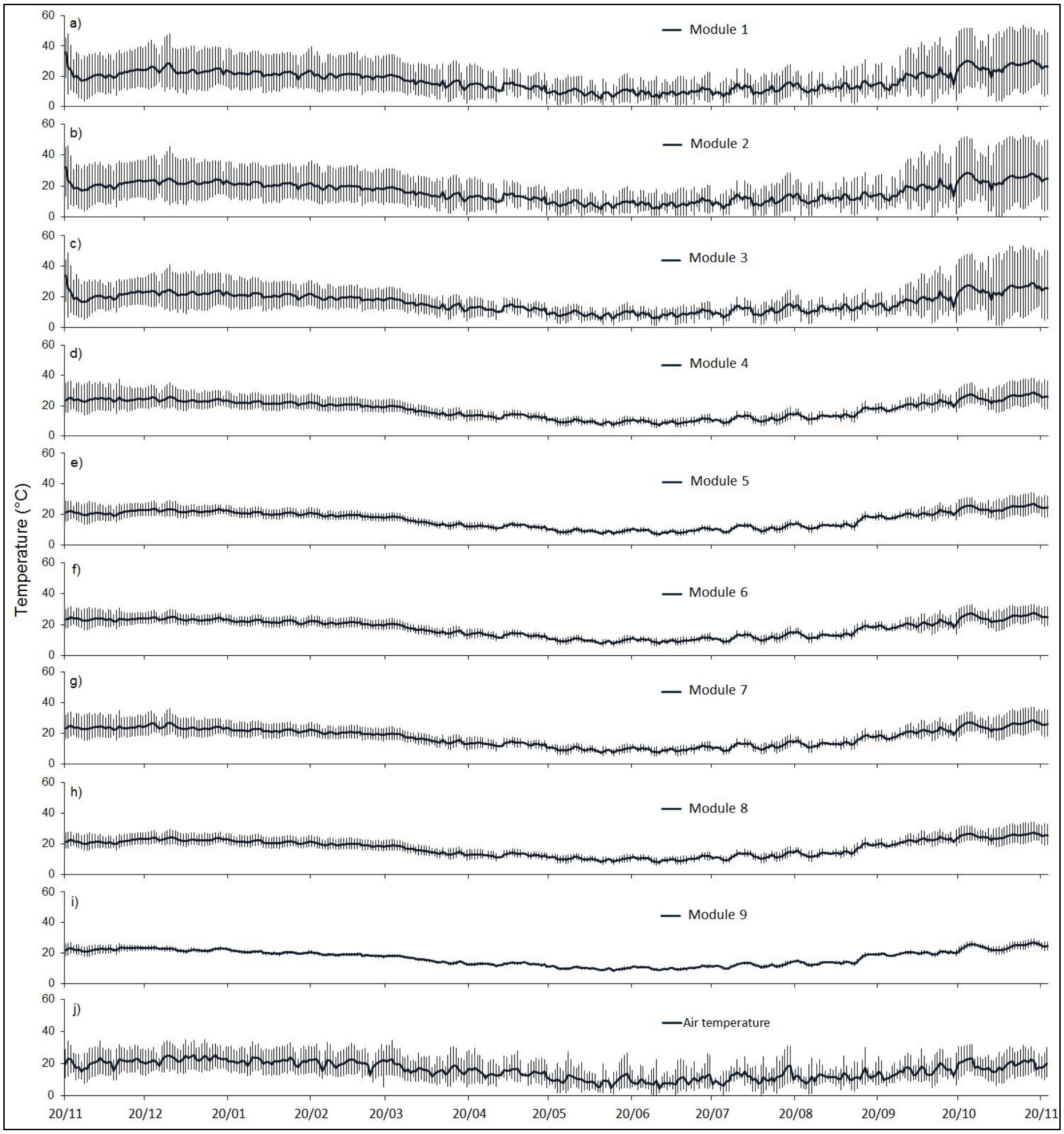

Figure 4-2. Daily thermal oscillation and mean temperature in different green roof modules with substrate depths of 5 cm (a, b, c), 10 cm (d, e, f, g, h), and 20 (i), as well as air (j). Substrate temperature was measured at half substrate depth. Air temperature is the reference temperature for substrate temperature behavior. The 5-cm depth modules exhibited higher daily thermal oscillation than air whereas 10-cm and 20-cm depth modules exhibited a reduced thermal oscillation.

These results are of high significance, as the temperatures reached by the substrate in shallow green roofs due to high insolation and severe drought is a main concern when using this type of technology in semiarid climates (Nektarios et al., 2011). First, and regardless of the water content in the substrate, a temperature below 50°C in the root zone is required for plant survival (Larcher et al., 2010). Second, a high temperature in the substrate affects plant sustainability by evaporating the stored water more rapidly, thus reducing the water available to plants and increasing the need for irrigation. Finally, high temperatures can affect the properties of the different layers of the green roof such as the geotextile, drainage system, and anti-root membrane. A typical temperature threshold for these elements is 50°C (Cosella-Dörken Products, Inc., Sika S.A.). For example, the anti-root membrane used in this study had a temperature range viability from -30°C to 50°C.

4.3. Substrate water content

Water content is an important parameter that requires more attention in summer and spring because of the atmospheric demand, high solar radiation and air temperature, low relative humidity and the absence of precipitation. These factors make irrigation necessary during these seasons. In contrast, in autumn and winter these conditions are less severe (Figure 4-1b), and irrigation is not needed because the volumetric water content (VWC) is higher than 0.15 $m^3\ m^{-3}$, which is the permanent wilting point value for this substrate. The VWC in the three 5-cm depth modules is shown in Figure 4-3a. During the first three months after planting, the irrigation was scheduled to provide high VWC in all the modules to promote the plant establishment and development. Thus, a large amount of water was added, especially in the 5-cm depth modules, to keep them above the permanent wilting point. Nevertheless, from December 12, 2013, to January 20, 2014, the VWC in modules 1 and 2 was $\leq 0.2\ m^3\ m^{-3}$, which is explained by the high atmospheric demand (Figure 4-3a). In fact, irrigation was used mainly to cool down the substrate by evaporation rather than to increase the VWC.

The VWC in 10-cm depth modules is shown in Figure 4-3b. The five modules showed the same behavior, with the VWC increasing because of the irrigation or rainfall and decreasing because of the atmospheric demand. On average, module 6, with a 30-L m^{-2} WRC retainer, exhibited the highest VWC in the study period. Module 5, with a 4-L m^{-2} WRC retainer, and module 8, without a drainage or retention system, showed nearly the same performance in terms of VWC. The largest differences were observed in the last months of the study with differences smaller than 0.05 m^3 m^{-3}. Module 7 showed the lowest VWC because it had the highest drainage capacity (161 L min^{-1} m^{-1}). However, despite the differences observed, the VWC was maintained at a suitable level for plant survival, except during the last month, when the VWC dropped below the permanent wilting point in all modules (Figure 4-3).

More abrupt changes in VWC were observed in modules 1 and 2 (5-cm depth). Figure 4-3a and Figure 4-4c show that the 30 L m^{-2} WRC retainer provides a stable VWC and adequate values above permanent wilting point. The retainer in module 3 was able to maintain a stable VWC very close to that of module 6, which had the same retainer but 10-cm depth substrate. On the other hand, the VWC in 5-cm depth substrates is more variable when the 4 L m^{-2} WRC retainer was used (module 2, Figure 4-3a). This was different from module 5, which had the same retainer but 10-cm depth substrate (Figure 4-4b). In fact, 5-cm depth green roofs were more affected by the atmospheric demand, which was improved by the retainer used in modules 3 and 6, as shown in Figure 4-4c. In general, green roofs with 10-cm and 20-cm depth sustained adequate and stable levels of VWC.

During the last two months of this study, the vulnerability of each green roof module to water stress was assessed. In the late days of winter and early days of spring (from September 17, 2014), atmospheric demand increased considerably causing a decrease of 0.28 m^3 m^{-3} in VWC in 19 days in module 1, 0.18 m^3 m^{-3} in 23 days in module 4 and 0.1 m^3 m^{-3} in 37 days in module 9. This promoted a water stress in the plants, resulting in changes in the leaf color and reduction in surface coverage. As shown in Figure 4-3 and Figure 4-4, the thinnest substrate reached the maximum moisture content in winter and autumn but also critical minimum values in spring and summer. At the beginning of the experiment, the irrigation was provided *ad libitum* because the purpose was to provide the optimal conditions for plant establishment, with more water than usually is needed due to the atmospheric demand. Only after that, the irrigation was reduced to match the evapotranspiration in each module. In the last 38 days of this study (October 15, 2014 to November 21, 2014), irrigation was activated at a rate according to atmospheric demand (approximately 6 mm). However, this irrigation program reduced only the rate of decay in the VWC, which indicates that the water was mainly used to cool down the substrate by evaporation.

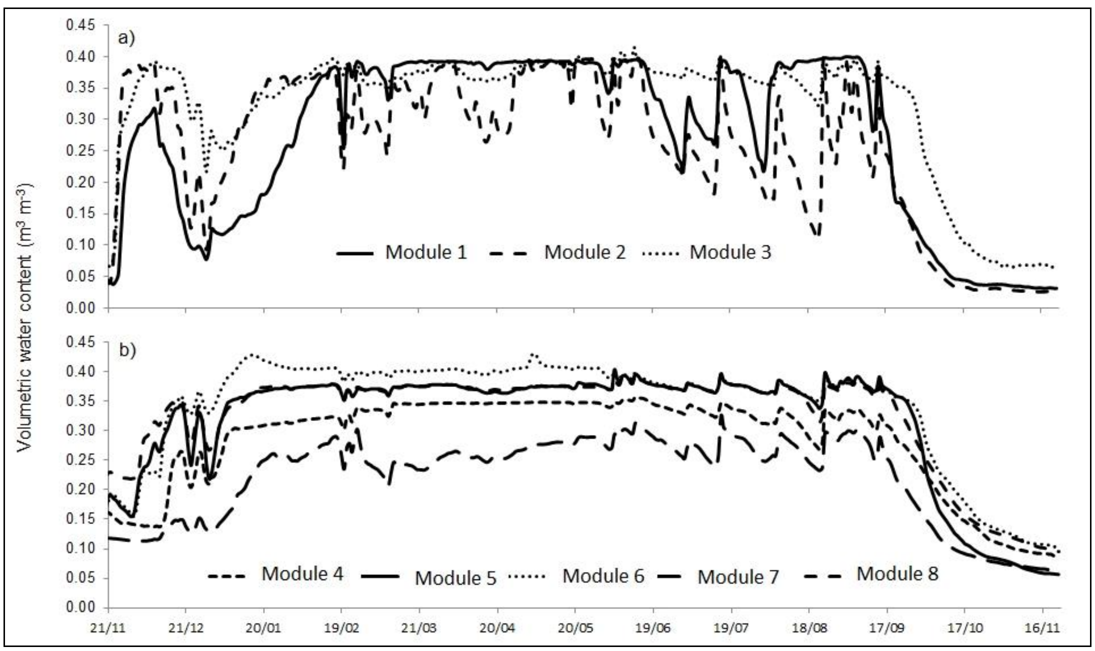

Figure 4-3. Mean daily volumetric water content in the three 5-cm depth green roof modules (a) and in the five 10-cm depth green roof modules (b). The same volumetric water content variations were observed for the 10-cm depth modules, as compared to those measured for the three 5-cm depth modules.

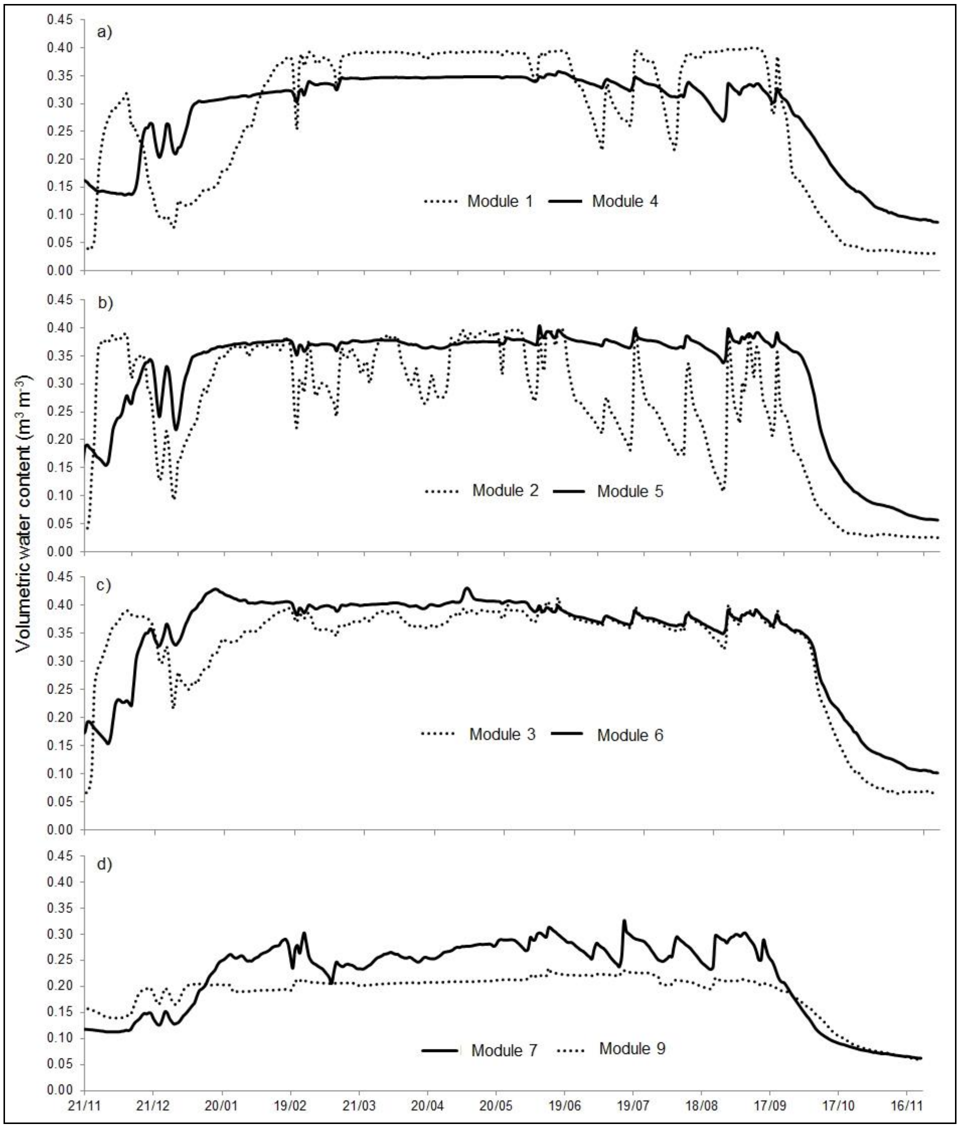

Figure 4-4. Volumetric water content recorded in green roof modules with the same drainage or retention system but different depth. This figure shows 5-cm depth versus 10-cm depth modules (a, b and c) and 10-cm depth versus 20-cm depth modules (d). For instance, the module 2 in figure (b) showed rapid changes in the volumetric water content compared to module 5. In contrast, figure (c) shows that these changes reduce when the module is changed by using a retainer that makes both lines almost equal along the entire season.

In the 10-cm depth green roofs modules, the VWC in the five modules were similar; thus the two retention layers (modules 5 and 6) performed as the two drainage system used (modules 4 and 7) and the module without drainage or retention system (module 8). However, in 5-cm depth green roofs, the retainer with the highest retention capacity performed the best in terms of maximizing VWC and reducing its variation in the study period. Savi et al. (2013) also reported a reduction in the positive effect related to the water retention layer as the substrate depth increases. Unfortunately, the higher VWC in the modules with a water retainer layer was not enough to reduce the substrate temperature oscillation in the 5-cm depth green roofs modules. Consequently, as reported by Williams et al. (2010), extensive green roofs with substrate depths thinner than 10 cm are unlikely to be sustainable and would not be recommended for arid or semiarid climates.

4.4. Temperature and substrate water content interaction

Previous studies have been conducted to model green roofs in terms of heat and mass transfer (Djedjig et. al, 2012; Tabares-Velasco and Srebric, 2012). Two of the main processes in these models are latent and sensible heat fluxes, which reduce green roof energy load and therefore substrate temperature. For that reason, due to the high atmospheric demand in the study site during summer and spring, irrigation was increased in the green roof with the purpose of increasing volumetric water content and thus reducing substrate temperature.

Some unexpected result was obtained on days with high atmospheric demand. Figure 4-5 shows module 1 substrate properties on December 29, 2013. Despite the six 7.5 mm pulses applied to reduce substrate temperature. The volumetric water content did not increase, and the substrate temperature reached up to 48.3°C. Energy load in the substrate surface was so high that irrigation was evaporated before wetting the substrate. Djedjig et al. (2012) showed that unirrigated green roofs could reach instant maximum temperatures from 45 to 53°C at 2 cm below soil surface during summer in a temperate climate in France. In semiarid or arid climates, substrate surface can easily reach temperatures beyond 55°C in unirrigated green roofs.

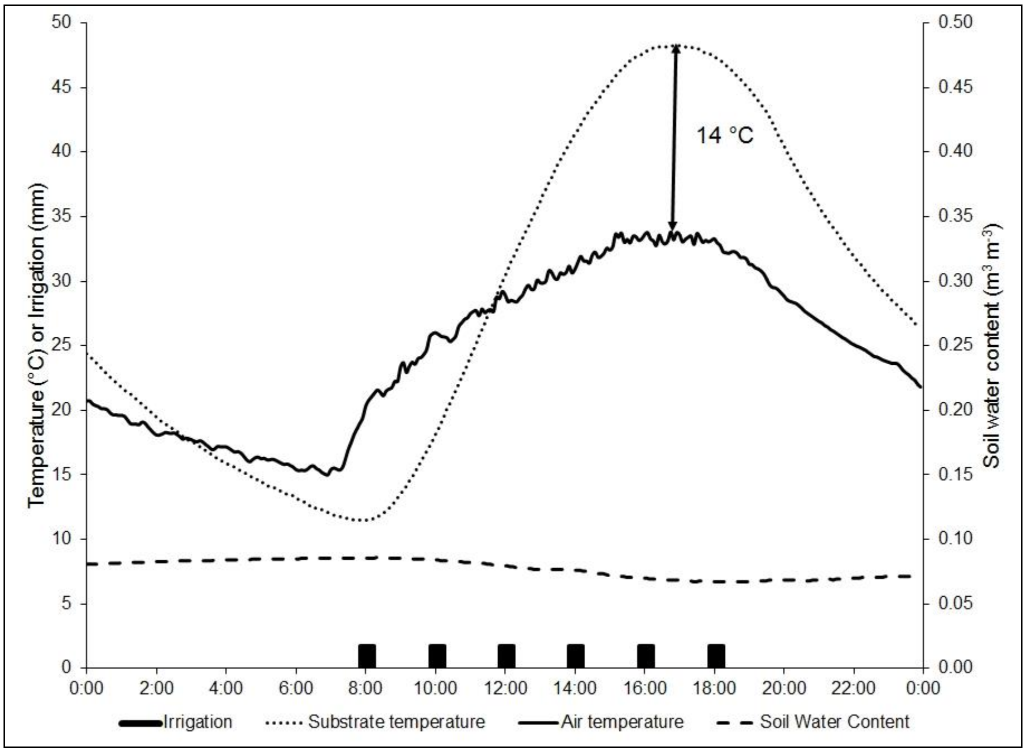

Figure 4-5. Water content and substrate temperature in module 1 on December 29, 2013. Maximum substrate temperature was 18°C higher than maximum air temperature and soil water content was not affected by irrigation.

Figure 4-6 shows the water content and temperature in the substrate with module 9 on December 29, 2013. Again, despite the four 15 mm irrigation pulses applied, volumetric water content was not affected (Figure 4-5). Irrigation in this case was mainly intercepted by plant leaves, which covered almost 100% of green roofs surface (Appendix 4 and Appendix 5). The remaining water was partly evaporated.

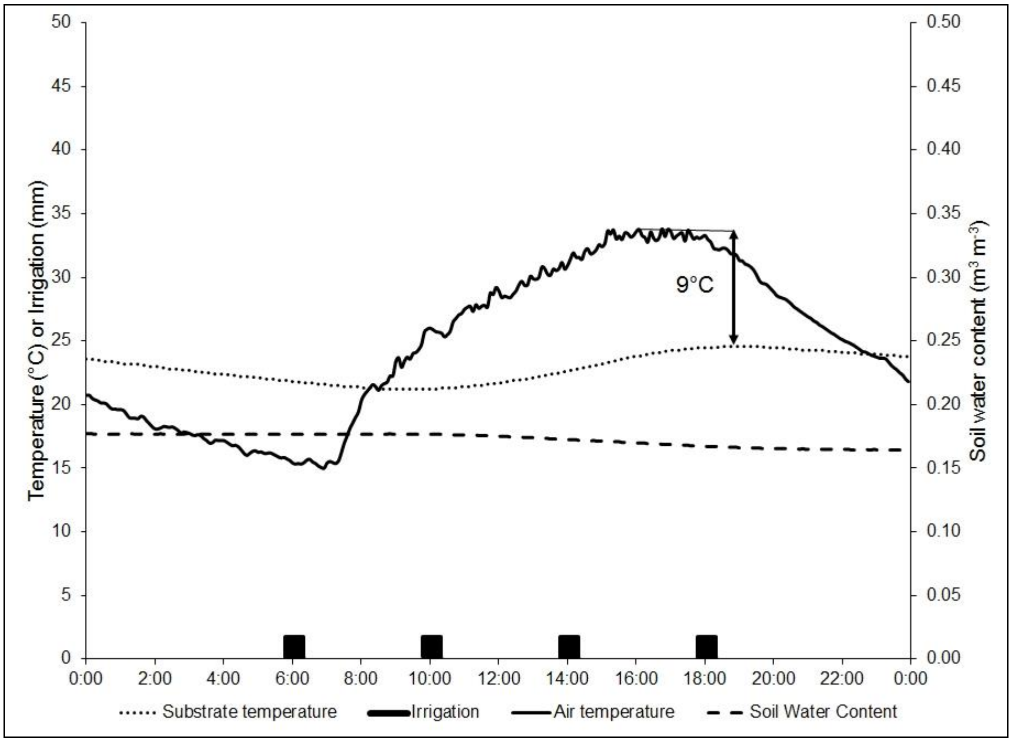

Figure 4-6. Water content and substrate temperature in module 9 on December 29, 2013. Substrate thermal oscillation is less than 5°C while air thermal oscillation was near 20°C. Soil water content was not affected by irrigation.

Green roofs with 10-cm depth (modules 4 and 6) had higher volumetric water content than module 9 (Figure 4-6 and Figure 4-7) because of the lower plant surface coverage and the corresponding smaller plant water interception. Thus irrigation wet the substrate and the green roofs solar radiation energy loads were reduced. The 0.12 m^3 m^{-3} difference in volumetric water content between modules 4 and 6 is explained by the retainer used in module 6, which absorbed water drained and subsequently returned it to the substrate by capillary action.

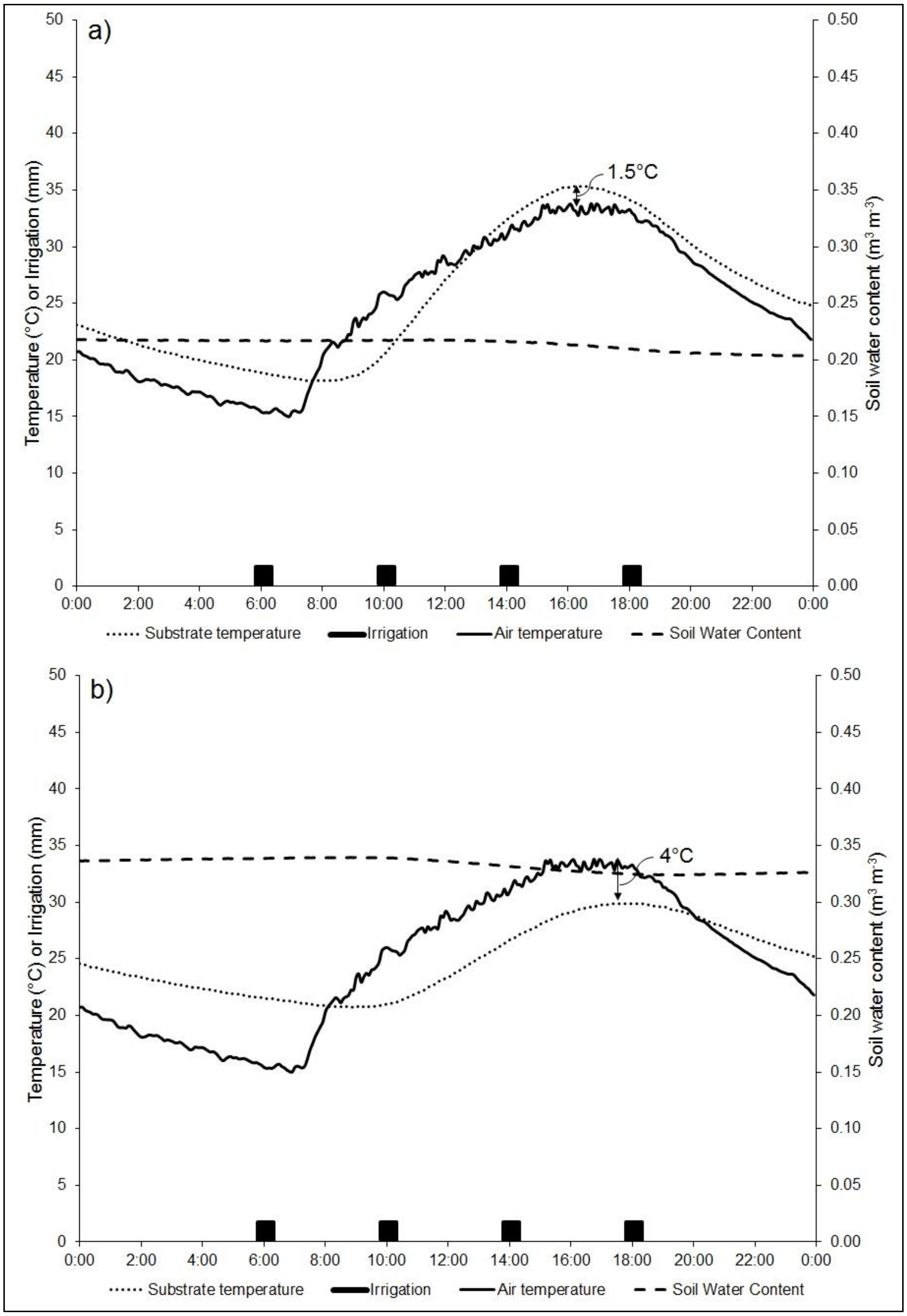

Figure 4-7. Water content and substrate temperature in module 4 (a) and module 6 (b) on December 29, 2013. In both cases water content was not affected by the irrigation but there was a difference of 0.12 $m^3 m^{-3}$ in the water content.

4.5. Plant survival and green roof surface coverage

The two plant survival analysis were done to analyze the fate of the plants of each type of *Sedum* planted on the green roofs (Table 4-2).

Table 4-2. Number of each type of sedum planted on each green roof module.

Type of *Sedum*	Module								
	1	2	3	4	5	6	7	8	9
S. kamtschaticum and S. hybridum	57	55	58	54	54	57	54	58	53
S. sexangulare	28	27	28	29	34	29	31	30	28
S. spurium	28	28	27	31	29	28	33	28	26
S. reflexum and S. rupestre	54	57	56	56	53	55	53	57	59
S. album	29	29	27	26	26	27	25	23	30

The percentages of plants alive one and seven month after plantation are shown in Table 4-3 and Figure 4-8. There were high rates of plant survival in the first survey. As overall, 91% of the *Sedum spp.* for the entire facility with all the modules. The minimum percentage was observed in module 1 (83%) while the maximum was observed in module 4 (98%), where only three plants died in the first month. All of the *Sedum* species behaved similarly showing a survival plant rate between 90% and 93%.

Although Table 4-3 shows a 3% difference between modules 6 and 9 in plant survival, it does not mean that both green roofs looked similar or had a 3% difference in plant surface coverage. In fact, from the beginning of the study the plant surface coverage in module 9 was larger than for the other modules (Figure 4-9). Plants in module 9 were not only alive but also larger. Furthermore, Figure 4-9b and Figure 4-9c show little differences in surface coverage between module 1 and 6, but in terms of plant number, module 6 had 21 more plants than module 1 (i.e. near the 10% of the number of the *Sedum* planted at the beginning of the study).

Unlike the first survey, the second measurement showed important trends in plant survival. Overall 77% of all plants planted in LIVE survived, with the lowest rates being observed for the 5-cm depth green roofs (from 66% in module 1 to 77% in module 2). This is explained by the high temperatures reached by the substrate during the spring-summer season, which stressed the plant and eventually killed several of them (Figure 4-10a). Despite its optimal conditions for plant development (i.e. volumetric water content always above permanent wilting point and temperature ranging between 8°C and 30°C) module 9 showed a 76% of plant survival. Since January 2014, module 9 had full surface coverage (Figure 4-10c), which implies the occurrence of natural selection, and thus larger plants hide sunlight to the others. Higher rates of plant survival were found in 10-cm depth modules, from 73% in module 7 to 85% in module 4. Furthermore, all these green roofs showed similar surface coverage. Figure 4-10b shows that plant growth in module 6 was better than in module 1 but not as good as module 9.

Module 1 lost half of its plants with an average of 51% of survival. The 87% of all *S. sexangulare* planted in LIVE survived, in fact, module 4 and 6 showed 100% of survival. Total plant survival was also observed in module 5 for the *S. album* species.

Table 4-3. Survival of *Sedum* species for different green roof modules. Total plant survival rates were 91% and 77% one and seven month after plantation. While long term overall plant survival rate in the 9 different modules varied from 66% to 85%, plant survival rate among the *Sedum* species varied from 71% to 93%.

Design Module	*Sedum* species											
	S. kamtschaticum and S. hybridum		*S. sexangulare*		*S. spurium*		*S. reflexum and S. rupestre*		*S. album*		Total	
	Date		Date		Date		Date		Date		Date	
	Oct-2013	April-2014	Oct-2013	April-2014	Oct-2013	April-2014	Oct-2013	April-2014	Oct-2013	April-2014	Oct-2013	April-2014
	%											
1	82	51	86	86	86	68	80	74	83	66	83	67
2	100	76	78	78	100	71	98	77	97	83	96	77
3	88	60	89	89	85	63	88	50	93	93	88	66
4	96	65	100	100	100	94	98	88	100	96	98	85
5	96	83	88	82	100	79	91	72	100	100	94	82
6	91	70	100	100	96	86	93	82	89	89	93	83
7	89	71	93	88	92	66	86	70	84	76	89	73
8	88	83	77	73	93	93	89	88	100	78	89	84
9	96	60	93	93	92	54	97	86	100	87	96	76
Total	92	71	90	87	93	73	90	75	93	83	91	77

Several *Sedum* species have been tested and proved to be drought tolerant on green roofs in the U.S. (Getter and Rowe, 2006). Among the *Sedum* species used in this study, Getter and Rowe (2006) found that *S. album* can survive more than 100 days without irrigation, and *S. kamtschaticum*, *S. reflexum* and *S. spurium* survived 88 days without irrigation in the temperate climate of Michigan. In the present study, *S. Sexangulare* has the best performed with 87% of plant survival and then *S. album* with 83% (Figure 4-8a). *S. kamtschaticum*, *S. reflexum* and *S. spurium* together with *S. Rupestre* and *S. hydridum* had plant survival rate of 75% or lower (Figure 4-8a). *S. album*, *S. reflexum* and *S. spurium* are recommended species for depths less than 7.5 cm for climates similar to southern Michigan while *S. kamtschaticum* might be a subsidiary specie, present at specific substrate depth but not very able to cover large areas (Durhman et al., 2007). In this study, *S. kamtschaticum* and *S. hybridum* had the highest plant survival rate in 10-cm depth modules (modules 5 and 8) with 83% of survival but showed the lowest total plant survival rate, 71% (Figure 4-8).

Finally, regardless the substrate many factors can affect plant survival and establishment (Monteruso et al., 2005; Dunnett and Kingsbury, 2010). (1) The initial planting method, (2) season of planting, (3) provision of an appropriate substrate and irrigation, and (4) effective maintenance during the establishment period. Therefore, there is a chance to increase the plant performance by optimizing some of these variables according to the local condition on each green roof project.

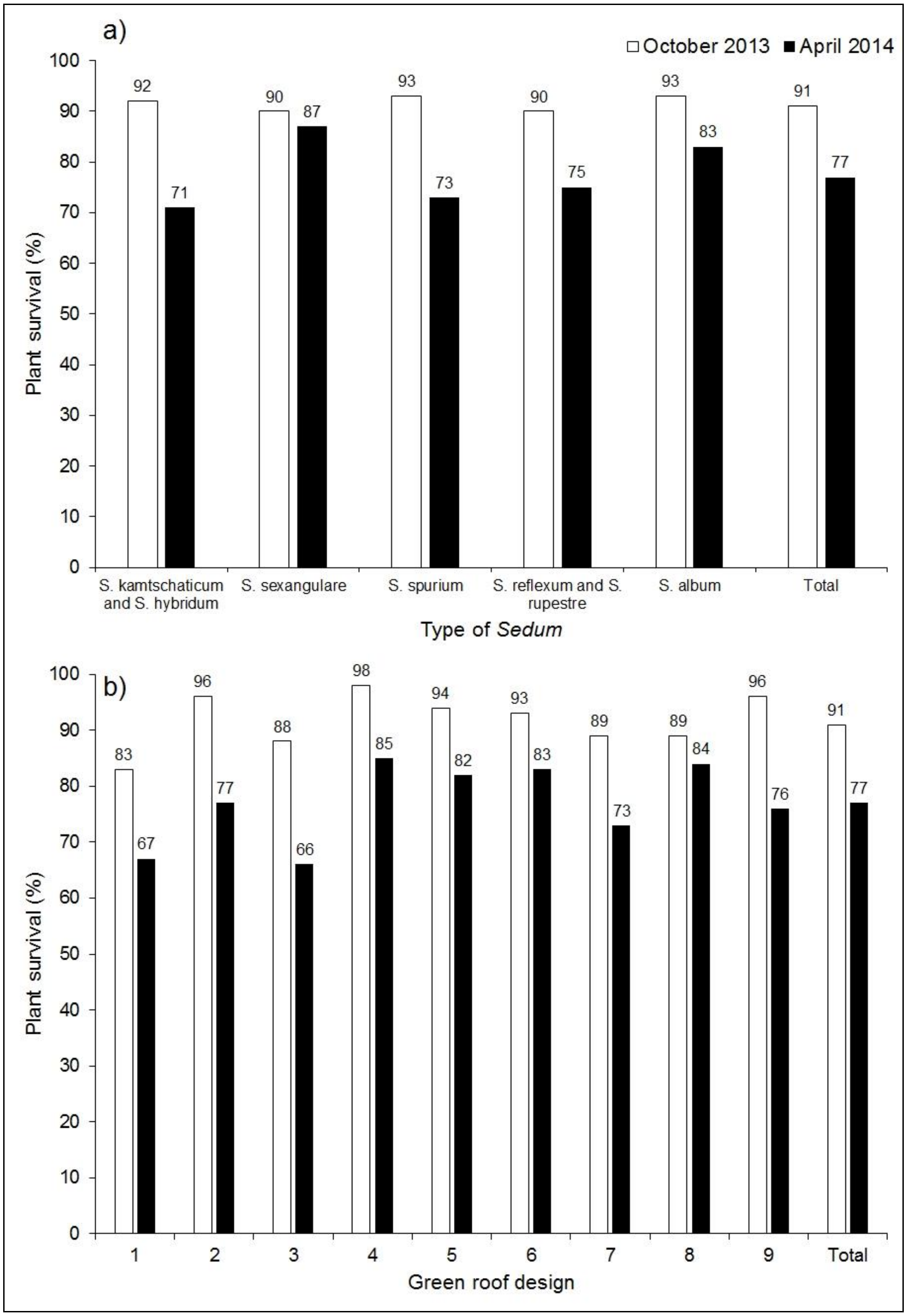

Figure 4-8. Plant survival of *Sedum* species in all green roof modules (a), and plant survival based on green roof module including for all *Sedum* species (b).

Figure 4-9. Pictures of module 1 (a), module 6 (b), and module 9 (c), on October 28, 2013. Just one month after plantation, the plant cover in module 9 was visibly larger than in the other modules.

Figure 4-10. Pictures of module 1 (a), module 6 (b), and module 9 (c), on June 26, 2014. Nine months after plantation, module 9 had full surface plant cover with large plants, module 6 had a homogeneous and near full plant cover with smaller plants than in module 9, and module 1 had small plants, heterogeneous and low plant cover.

4.6. Variability in the LIVE

Variability in green roof measurements was evaluated with the three replicates of module 8. This module had 10-cm substrate depth, between thinnest and the deepest green roof substrate studied. Replicates had the drainage system with the highest drain capacity. Therefore, substrate water retention capacity was not affected by the retainer and the results can be extrapolated to other green roof module in this study because of replicate distribution in the laboratory. Replicate 1 was at the south side of LIVE and received more wind, replicate 2 was at the north of the LIVE and received more insulation, and replicate 3 was in between of the other replicates (Appendix 2).

The analysis was performed in spring and summer seasons, which are the critical periods for green roof in semiarid climates. Results indicates that there is an average standard deviation of 0.46°C in the mean daily substrate temperature with a maximum of 1.59°C reported in December 2013 (two months after plantation). Substrate moisture content showed an average standard deviation of 0.038 $m^3\ m^{-3}$, with a maximum value of 0.076 $m^3\ m^{-3}$ reported in January 2014. While substrate temperature depends on depth, substrate moisture has a spatial variability, which depends on organic matter content substrate distribution, retention substrate properties and irrigation homogeneity. The latter factors should be taken into account specially when designing green roofs. Thus, the green roof has a homogeneous water content in the substrate and punctual VWC measurements are representatives for substrate moisture property.

In terms of plant survival, there was a standard deviation from 4% to 9% on each *Sedum* species and 6% for the total plants in the first survey. On the other hand, the standard deviation in the second survey for *Sedum* species increased to values from 8% to 16% while total value remained as 5% (Table 4-4). Figure 4-11 shows how replicates looked six-month after plantation. Even if all the plants in the three replicates had similar growth, replicate 1 was more exposed to wind speed than 2 and 3. A lack of plants is observed in the upper right side of picture (a) as wind speed affected normal irrigation of this area.

Table 4-4. Plant survival of each type of *Sedum* species on replicates of module 7.

		Replicates		
		1	2	3
		%		
October 2013	*S. kamtschaticum and S. hybridum*	93	87	86
	S. sexangulare	100	93	87
	S. spurium	100	92	84
	S. reflexum and S. rupestre	94	85	80
	S. album	88	91	74
	Total	95	89	83
April 2014	*S. kamtschaticum and S. hybridum*	57	77	78
	S. sexangulare	100	83	81
	S. spurium	83	67	50
	S. seflexum and S. rupestre	67	79	65
	S. album	77	91	59
	Total	73	78	68

Figure 4-11. Pictures of the three replicates 1 (a), 2 (b) and 3 (c) for module 7 used to evaluate variability in LIVE. Pictures were taken on March 25, 2014. Replicates 2 (b) and 3 (c) had a similar surface coverage but replicate 1 (a) had a bare substrate space because irrigation was irregular in this area due to wind effect.

5. CONCLUSIONS

This study investigated the plant and substrate performance of nine green roof modules with different layering and three substrate depth (5, 10 and 20-cm) and evaluated them on the basis of green roof temperature and water requirements in the semi-arid climate of Santiago, Chile. In this harsh environment, the atmospheric conditions in spring and summer expose the green roofs to dryness and high solar radiation and air temperature. The maximum substrate temperature reached values beyond the 50°C in thinner green roof substrate, which is close to or higher than the heat-stress threshold temperature of some plant species. This temperature also exceeded the thresholds for some layers of the green roof, reducing their life span and durability.

This study demonstrates that increasing substrate depth is an efficient way to reduce the temperature in the root zone. The 10-cm and 20-cm depth modules had a dumping effect on the substrate temperature compared to air temperature, while 5-cm depth modules showed an amplifying effect, yielding a substrate temperature 26°C higher than the maximum air temperature in spring and summer. By contrast, the 10-cm and 20-cm depth green roofs were able to keep adequate and stable levels of water content during the entire study period. In 10-cm depth module the use of a drainage or retention system did not have a remarkable impact on volumetric water content. The 5-cm depth green roof modules were more affected by the atmospheric demand, which was compensated by using a high capacity water retention fabric. However, in the same 5-cm depth modules, increasing the irrigation rate or improving the substrate water holding capacity did not keep the maximum substrate temperatures below 50°C on days with high atmospheric demand.

Among the nine green roof modules evaluated in this study, a 77% of plant survival was obtained considering a mix of seven *Sedum* species. The minimum plant survival was 66% in the 5-cm depth green roof module. On the other hand, the maximum plant survival was 85% in the 10-cm depth green roof module. *S. sexangulare* was the species with the highest survival rate (i.e. 87%). On the other hand, *S. kamtschaticum* and *S.*

hybridum were the species with the minimum survival rate (i.e. 71%). Therefore, the *Sedum spp.* most recommended to be used in 5-cm to 20-cm depth green roofs in semiarid climate was *S. sexangulare* and the less recommended were *S. kamtschaticum* and *S. hybridum.*

Plant survival and green surface coverage indicate that after looking at the number of plants alive, it is important to monitor plant growth and stress condition. Indeed, the benefits of this technology is accomplished under total plant surface coverage. In this study, a low plant survival was explained by two reasons. First, due to the high insolation, high temperature, low relative humidity and lack of rainfall in spring and summer seasons, several species died and those that survived did not grow enough to completely cover green roof surface. Second, the optimal substrate conditions favored the development of some *Sedum* species, which grew in detriment to the other species. In this case, full surface coverage was usually observed. However, this is a study of combined species, not a study of separate species as species cannot be independently analyzed, since this is how it is used in actual green roof.

Consequently, a proper design is crucial when using this kind of technology in semiarid climates. The results of this study must be considered in future green roof projects to make a better selection of the green roof layering and vegetation. This is crucial to assure a sustainable water management in urban environment in semiarid climate.

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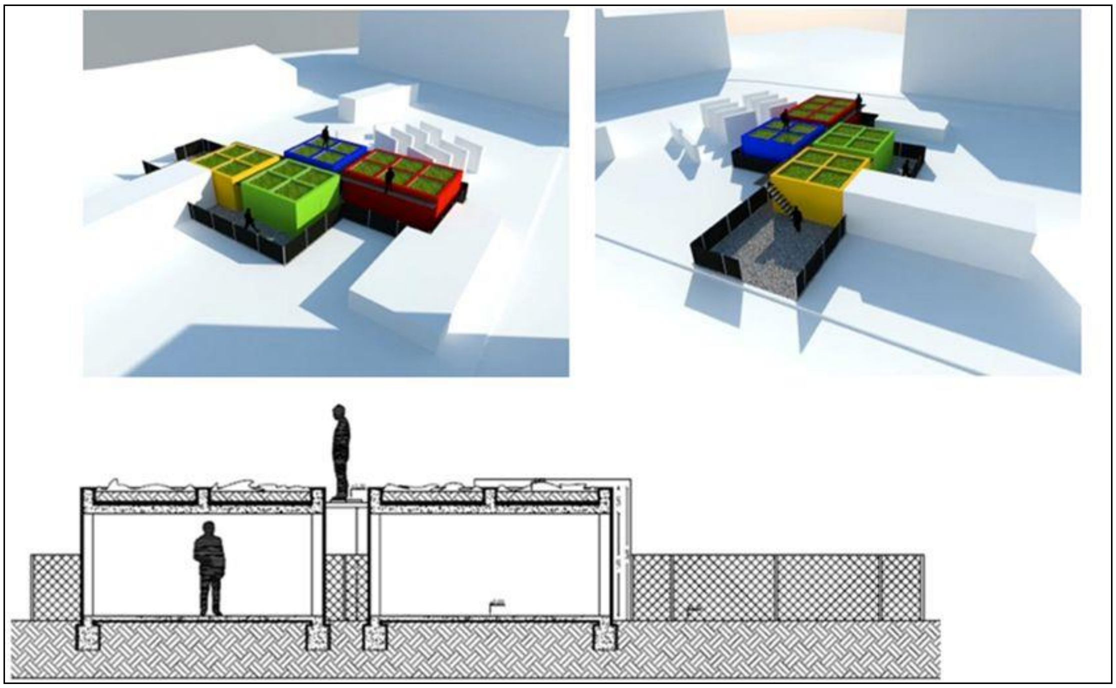
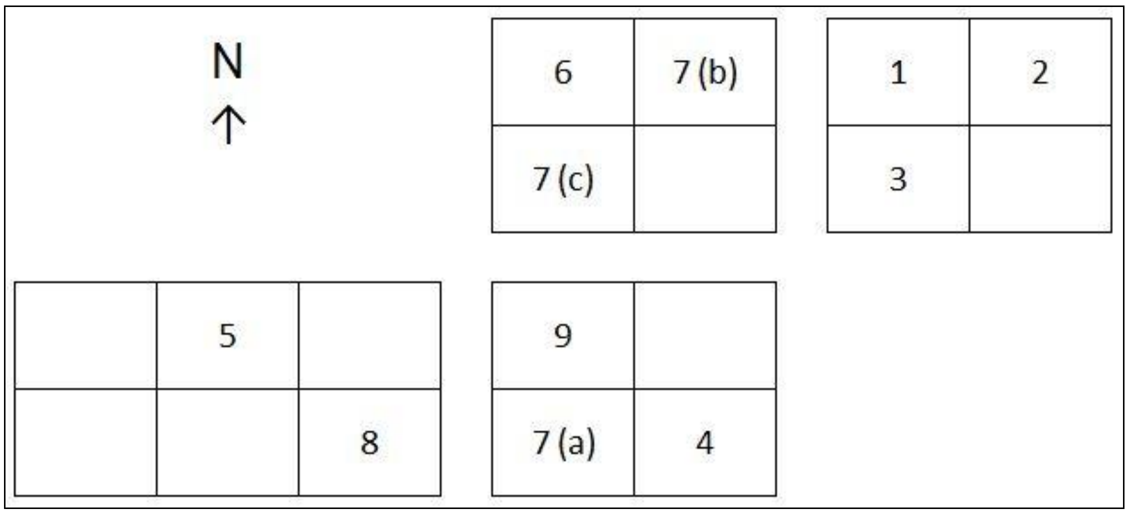
APPENDIXES

Appendix 1. Representation of LIVE setup. This is a reinforced concrete construction of 2-m high that simulates the top floor of a residential building.



Appendix 2. Top view of the distribution of the different modules in LIVE.



Appendix 3. Green roof modules based on retainer or drainage system, geotextile and anti-root membrane. Modules 1, 4, 7 and 9 required a geotextile and an anti-root membrane because did not have these properties, while retainer in modules 2, 3, 5 and 6 included geotextile and anti-root properties.

		Component			
Design Module	Substrate depth (cm)	Geotextile	Drain	Retainer	Anti-root membrane
1	5	Delta®-Biotop	Delta®-Drain	-	Delta®-Root Barrier
2	5	-	-	Sika® Sarnavert Aquadrain 550	-
3	5	-	-	Vydro®	-
4	10	Delta®-Biotop	Delta®-Drain	-	Delta®-Root Barrier
5	10	-	-	Sika® Sarnavert Aquadrain 550	-
6	10	-	-	Vydro®	-
7	10	Delta®-Biotop	Delta®-Floraxx	-	Delta®-Root Barrier
8	10	-	-	-	-
9	20	Delta®-Biotop	Delta®-Floraxx	-	Delta®-Root Barrier

Appendix 4. Substrate profile four months after planting in module 9. Vegetation layer was much dense and the limits of each plant disappeared. The root zone was clear and occupied the upper 8 cm of the substrate layer.

Appendix 5. Picture of module 9 in November 2013 (a), December 2013 (b), and January 2014 (c). As can be observed, module 9 plant coverage was full four months after planting.

Appendix 6. Daily temperature oscillation in all modules including the three replicates of module 7. The figure shows daily oscillation temperature divided in quartiles and the mean value as the white circle. For example the maximum daily oscillation in module 2 was 46°C, this means that during the study period the maximum difference between maximum and minimum substrate temperature was 46°C. In module 2 the quartile 3 is 24°C, this means that 75% of the days, daily oscillation was less than 24°C.