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Exploring the Potential of Mexican Crassulaceae Species on Green Roofs

by

Elisa Olivares Esquivel

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Abstract

Extensive green roofs (roofs with low diversity surface vegetation and a thin layer of porous substrate) generally utilize a very narrow range of available plants in their designs; namely *Sedum* species. These plants share critical characteristics of drought resistant, low nutrient demand, vegetative propagation, and simple shallow root systems- making them highly tolerant to the extreme environment of the extensive roof. *Sedum* species dominate the extreme green roof plant palette as these are low maintenance, but their monotonous colour, texture and structure, combined with their minimal ecosystem services, result in the creation of green roofs of low aesthetic value and few environmental benefits. *Sedum* species belong to the Crassulaceae family of mainly drought tolerant succulent plans. Mexico is a bio-diverse hotspot of Crassulaceae. By developing a plant selection methodology based on a combination of climatic classification systems with temperature and precipitation information, a broad range of Mexican Crassulaceae species are identified as potential candidate species to improve and diversify the extensive green roof palette. This selection methodology is applied to Mexican Crassulaceae for two specific study sites of highly contrasting climates (Cwb and Cfb according to the Köppen map of climate classification) in Mexico City, Mexico and Sheffield, UK respectively. Candidate species performance and survival are investigated in screening and competition experiments over several growing seasons comparing plant responses to substrate depth and planting season. These species response are then used to determine the efficacy of the plant selection methodology in the identification of possible candidate species for expanding the extensive green roof plant palette.

Dedication

To my parents Lolita and Eduardo Olivares and to my brother Eduardo Olivares. Although they are not here anymore they left their love and passion for life.

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Chapter 1 Exploring the potential of Mexican Crassulaceae species on green roofs: An Introduction

1.1 Background

Today the urban areas hold 54 percent of the world's population, and it is projected that by 2050 this number will increase to 66 percent (United Nations, 2014). Cities range from small settlements of 500,000 inhabitants to mega-cities with more than 10 million inhabitants (United Nations, 2014). This rapid growth of cities is usually unplanned; therefore there is an urgent need for "[…] economically, socially and environmentally sustainable development […]" in urban and rural areas (United Nations, 2014)

The high densities of inhabitants, the impermeable surfaces of the urban terrain, transportation, industry and other factors result in high levels of air, water and noise pollution, excess water runoff, increased local temperatures, loss of habitat for wild-life, high levels of stress, diseases in the population, and other problems. Inside the urban areas we can find green infrastructure assets (i.e. areas with water or vegetation). These areas can deliver multiple functions for the cities. Some of these functions are ecosystem services that are usually divided into four kinds: Supporting and Habitat, Provisioning, Regulating and Cultural (EEA, 2011, Landscape Institute, 2009, WHO, 2005).

Supporting and Habitat services provide shelter to fauna and floral biodiversity (Gómez-Baggethun et al., 2013). Provisioning benefits derive directly from an ecosystem and include resources such as food, fresh water and medicines. Regulating services are those obtained by processes such as water and air purification, runoff mitigation, pollination and seed dispersal, local climate regulation, and much more. Cultural benefit examples can be related to aesthetics, historical and traditional use, as well as in stress relief and mental well-being or local values and social cohesion (Gómez-Baggethun et al., 2013). Parks, trees, lakes, ponds, house gardens, fountains, green roofs, and any green and blue area usually provides several of these functions.

Green roofs are systems that have evolved from simple gravel layers on the roof with the single function of protecting a waterproof layer, to systems that can provide multiple ecosystem services to cities. **This research will explore the potential of Mexican Crassulaceae species in these green roofs systems in two very different climates**.

- **Warm temperate, winter dry, warm summer** (**Cwb** in the Köppen-Geiger system) with a case study in Mexico City

- **Warm temperate, fully humid, with warm summer** (**Cfb** in the Köppen-Geiger system) with case study in Sheffield, UK

1.2 Green roofs across the world: a brief history

The cultivation and use of plants on top of roofs is a very ancient practice, either for necessity (as some research suggests, turf roofs go back to Neolithic settlements in the European North Atlantic area to protect houses from cold and rain (Loveday, 2006, Urbanczyk, 1999)) or for pleasure, like the gardens of the Assyrian king Sennacherib in Nineveh; otherwise known as the Hanging Gardens of Babylon (Dalley, 1993). Nevertheless, green roofs as known today, started as a protection cover for the tar paper waterproof sheeting system used in roofs in the XIXth Century systems which consisted, as its' name suggests, of layers of paper and tar. Gravel, sand and sod were disposed on top of the waterproof layer to prevent fires and damage due to solar radiation, and with time, plant communities started to develop on these layers (Köhler, 2006, Köhler and Poll, 2010).

Today the concept *green roof* usually refers to the systems that have evolved from those tar-paper gravel roofs. The studies of the plant communities, growing on these early green roofs, set up the route to re-greening the cities of Germany in the 1980s (Köhler, 2006). These were the first steps to the development of systems with low input of resources and maintenance, to provide environmental benefits to the city. Today, green roofs are categorized by their depth and the types of plant species they support. Two extremes of the spectrum are intensive and extensive green roofs. Nevertheless there are different systems that share elements of both extremes, such as semi-extensive or semi-intensive and bio-diverse roofs. All of them provide in different degrees, multiple ecosystem services to the cities (Dunnett and Kingsbury, 2008, GRO, 2014, Oberndorfer et al., 2007, FLL, 2008).

1.2.1 Green roofs in the UK

The use of contemporary green roofs in the UK is steadily becoming more common. In the 1970s Brian Richardson set up a self-build green roof in his home in Herefordshire with local soil and turf and some *Sedum* and *Sempervivum.* The predominant grass community (*Festuca rubra, Anthoxanthum odoratum* and *Cynosrus cristatus*) has now survived over 26 years (Dunnett and Kingsbury, 2008).

As the UK´s cultural capital, London has had significant investment in green roofs. Modern green roofs started to be installed on various buildings, such as the Centre for Wildlife Gardening. This roof was constructed with a variety of substrates including chalk, loamy topsoil and gravel, and varying substrate depths from 50 to 100 mm. The roof was planted with upside down lawn turf and native wildflower seed mixes (Grant, 2006). In the Centre for Understanding the Environment in the Horniman Museum, a roof with low fertility 100 mm substrate was planted with a *Festuca-Agrostis* turf and plug plants such as *Campanula rotundifolia* and *Galium verum* (Grant, 2006).

Sedum roofs have been widely used in London with companies like Bauder installing more than 20,000 m^2 up to 2005 (Grant, 2006). In 2002, the first "Brown Roof" was constructed as part of the Species Action Plan to protect the endangered black redstart bird (*Phoenicurus ochruros*). This bird was seen breeding in brown field sites in London that were going to be regenerated. In order to provide a new habitat, "brown roofs" were designed and constructed in an attempt to mimic the brown fields, using rubble from the site (Gedge, 2003). Brown roofs did not become as successful as expected since flat *Sedum* roofs had a higher numbers and diversity of invertebrates than these sites (Kadas, 2006). Today improved guidelines for Bio-diverse roofs contained in the GRO Green Roof Code of Best Practice (GRO, 2014) provide more wild-life benefits.

Sheffield is also a centre of green roof best practice in the UK. An example of a successful "brown roof", or roof for biodiversity, is the green roof of Sharrow School in Sheffield. The substrate of this roof ranges from 100 to 500 mm depth. The roof recreates different habitats of the surrounding areas, such as calcareous grassland from the Peak District, urban brown field meadows, unmanaged areas for colonization, and a wet-land area. Other parts have been sown with different meadow seed mixes. The roof is the first green roof officially declared a Local Nature Reserve (Natural England, 2009, Dunnett and Kingsbury, 2008). Others examples of Sheffield green roofs include the green roof of the "Cube" a building near Sheffield Train Station, and several other green roofs on buildings of the University of Sheffield. The demonstration green roof of the Green Roof Centre of the University of Sheffield is of particular interest since it has been use to develop research on water runoff and different methods of planting.

1.2.2 Green roofs in Mexico

In Mexico the installation of modern green roofs started when the mayor of Mexico City, Cuauhtémoc Cárdenas, sent a group of researchers to Germany to learn about the modern green roof technology from the Humboldt University in Berlin. Jerónimo Reyes from the Botanic Garden of the National Autonomous University of Mexico (UNAM) and Gilberto Nava from the University of Chapingo pioneered the first projects in México City in 1999. Nevertheless, the general public was not ready to invest in green roofs because of fear of leaks and structural damage. Therefore the first buildings with green roofs were government offices. In 2005, Tanya Müller García founded AMENA, a Mexican association for the greening of roofs, which helps with the divulgation and promotion of green roofs in Mexico. In 2010 AMENA organized the World Green Roof Congress together with the World Green Infrastructure Network.

As all incentive to encourage the further installation of green roofs in Mexico City, as of 2008 there is a 10% reduction of Council Tax to owners of houses with green roofs. The discount is valid only if the green roof is established on at least a third of the total roof area of the house (Dircción de Reforestación Urbana, 2013). In personal communication with Mónica Celis Albor, deputy director of the Department of Reforestation and Pruning of the Secretariat of State for the Environment and Natural Resources of Mexico City, there are over 15,000 m^2 of green roof in the Federal District, with 60 % extensive, 30 % semi- intensive, and 10% intensive (Celis-Albor, 2013). Unfortunately, there is currently no register or database of the initial designs of existing green roofs, even though owners who want to claim the discount on council tax need to send their project for approval. This lack of planning information means little is known about the potential ecosystem services Mexico City green roofs maybe providing. Furthermore, there are no guidelines or regulations concerning the types of plant supplies unsuitable for Mexico City roof planting. This has resulted in the introduction of highly invasive alien species including *Kalanchoe* species which can compete with the native Crassulaceae.

1.3 Type of green roofs and their type of vegetation

1.3.1 Extensive green roofs

Extensive green roofs are the shallowest systems of all. Different authors differ in their opinion on the suggested depths, but usually they range from 2 cm to a maximum of 15 or 20 cm (Dunnett and Kingsbury, 2008, Oberndorfer et al., 2007). Because of the shallow layer of soil, these systems cannot hold a wide diversity of plants that can provide maximum cover, and therefore the common plants used in these systems are species naturally adapted to shallow substrates, low nutrients and rapid drainage. These include Crassulaceae species, alpine species, small bulbs, small herbaceous plants and grasses, as well as drought tolerant mosses and any drought tolerant plant species with a ground cover habit (Dunnett and Kingsbury, 2008, FLL, 2008). The installation of these green roofs can be performed with seeds, cuttings, plugs, plants or pre-grown mats. In terms of management, the extensive green roofs are designed to require the least possible input of resources and labour once installed. Usually these roofs are not intended to be accessible to people.

1.3.2 Intensive green roofs

The intensive green roofs, in comparison with the extensive green roofs, usually have deeper substrate, from 15 or 20 cm to more than 100 cm in depth (Dunnett and Kingsbury, 2008). Substrates of these systems usually have a higher maximum water holding capacity than the substrate for extensive green roofs (FLL, 2008). As a result, these systems can hold a wider variety of plant species, from herbaceous plants to shrubs and over trees. The management of these roofs is very intensive in terms or resources and labour and for this reason this type of roof is not favoured by developers.

1.3.3 Semi-extensive and Bio-diverse green roofs

The semi-extensive roof substrates usually have a range of 10 to 20 cm in depth. These systems are the middle path between extensive and intensive green roofs. Semi-extensive green roofs are designed to hold a wider variety of plant species and forms than the extensive green roofs; from succulents and slow growing plants to taller and more productive herbaceous species and grasses. In contrast with the intensive systems, the management of and input to these systems is low, as with extensive green roofs, even though they hold greater diversity of plant species and forms (Dunnett and Kingsbury, 2008).

The bio-diverse green roofs are systems designed with the aim to create habitats for wildlife. In terms of substrate these systems incorporate various depths, topography, bare and vegetated substrates and different water-holding-capacity substrates. This heterogeneity allows the growth of different plant forms and species on the same roof. The incorporation of wooden logs, rocks, bricks, ponds and other landscape features creates microhabitats on the roof that can shelter wild-life in general or can be targeted for specific species (Brenneisen, 2003, Baumann, 2006, Burgess, 2004, Kadas, 2006, Dunnett and Kingsbury, 2008, Gedge, 2003).

1.4 Benefits of green roofs

Green roofs can provide multiple benefits to cities depending on their design. The layers of substrate and vegetation can be customised to provide services for the reduction of common problems in the cities, such as loss of wildlife habitat, water runoff, heat island effects, air and noise pollution, etc. This does not imply that the installation of green roofs in the cities will alone solve the problems characteristic to urban areas, but their inclusion in the city planning can be an added part of the solution.

1.4.1 Biodiversity and wild life habitat

Some green roofs are specifically designed to enhance the biodiversity of the cities, as is the case with Bio-diverse green roofs, however even extensive green roofs can provide habitat for some wild species (Kadas, 2006). It is important to emphasize that the creation of habitats for wildlife on green roofs, does not function as an equivalent or a substitute for the habitats on the ground. Some species cannot access the roof environment, the small size of the roofs in comparison with the ground level space can limit a successful colonization, and/or plant species richness, and for some species the environment of the roof is too harsh (Brenneisen, 2006, Köhler, 2006). In some instances the roof can be detrimental, where its isolation can act as a trap for species that require different resources at different stages of life; in these cases alterations to the roof can help the species survive (Williams et al., 2014, Baumann, 2006).

In Switzerland and London as well as elsewhere green roofs hold species, from the Arachnid, Hymenoptera and Coleoptera taxa, some of which are listed as vulnerable to extinction in the Red Data Book (Kadas, 2006, Brenneisen, 2003). Pearce and Walters (2012) recorded six species of bats on Bio-diverse roofs in London, however the low presence of bats on *Sedum* roofs, showed these roofs are no different to conventional roofs for encouraging bat population. In Switzerland the improvement of green roofs has been studied to achieve the successful fledging of several ground-nesting birds species that are losing ground level terrestrial habitat and are now using green roofs to breed their chicks (Baumann, 2006).

1.4.2 Rainwater management

Green roofs can improve the urban management of rainwater by retaining water in their substrates and by the uptake of water by plants, thereby reducing and delaying water runoff. Even though the benefits at the large scale of cities can only be observed if a high proportion of roofs are greened, benefits can be seen at a smaller scale in houses and neighbourhoods, as Dunnett and Clayden (2007) point out. The water-storage capacity of the roof depends on several related factors such as depth of the substrate, substrate water holding capacity, roof inclination, type of drainage and filters, and the type of plant species and groups of plants growing on the system (FLL, 2008, Graceson et al., 2013, Mentens et al., 2006, Nagase and Dunnett, 2012). All these factors need to be tuned to maximize the water retention and evapotranspiration rate of the system and, at the same time, ensure the growth of healthy plants on the roof in each specific climate. Furthermore, the water storage capacity of the roof not only depends on the structural factors of the system, but it will fluctuate depending on temperature, wind, solar radiation and frequency of rain events (i.e. the climatic conditions of the particular site) (Stovin et al., 2013).

1.4.3 Energy efficiency of buildings

Green roofs have insulation properties that can help reduce the use of energy for heating the building during the winter and cooling it during the summer. However these properties, as with the rainwater management, depend on the characteristics of each one of the elements of the system (Liu and Minor, 2005, Castleton et al., 2010). In this case the substrate type and depth, soil heat conductance, evapotranspiration from substrate and vegetation, the leaf area index of the plants, and other factors are added elements that can help with the reduce energy use fort the heating and cooling of the building (Sailor, 2008, Sailor et al., 2012). For example Sailor et al. (2012) model energy consumption on roofs in different climates and found that increasing the vegetation density can reduce the electricity required for cooling the building during the summer, but it can increase the use of energy consumption during the winter due to the shading effect of the plants on the surface of the roof. In this case, as with the water management services, models are becoming an important tool to design efficient systems targeted for specific climates.

1.5 Green roof plant selection

All the layers of a green roof have an impact on each one of the services the system can provide. For this reason the elements of a green roof will vary in each case, depending on the services required, the climatic conditions of the site, the structure of the building, budget, etc. The vegetation layer is not exempt from this functionality, and the plant's survival, traits, and health, are added into the equation. Indeed, the choice of plants for the roof will determine the roof's environmental and ecological impact in the long-term. The methodologies for plant selection are designed to fulfil the survival and healthy growth of the plants in the extreme conditions of the roof, in addition to the multiple services or functions which plants can perform. Plant selection methodologies can incorporate information about plant communities from habitats similar to the green roof environment, as well as specific physiological traits that can provide specific environmental services to the city.

1.5.1 Plant selection for energy efficiency and water management

Methodologies of plant selection for cooling and water management are related, since one of the mechanisms behind both services is the evapotranspiration rate of the plants and substrates involved. In terms of cooling, some studies look at plant morphological characteristics such as waxes, trichomes, colour of leafs or height of canopy as traits that may help to reflect excess solar radiation. For water management, an individual plant's water use, uptake and transpiration are of particular importance.

Dunnett et al. (2008a) ran two experiments to investigate how vegetation composition affects water runoff in Sheffield, UK. The first experiment was set up in beds raised 1.5 m from ground level in a yard receiving rain water and had been watered only when conditions were very dry. There were four species of three different taxonomic groups: grasses, sedges, and forbs from calcareous communities, planted in densities of 12 plants per bed, in 100 mm depth of rendzina soil from the Peak District National Park. Although the primary objective of the experiment was not the study of the green roof's properties, its' similarities with these systems has provided valuable information about them. A second experiment was set up in small trays in a greenhouse as a control and consisted of forbs, grasses and *Sedum* as the taxonomic groups used in high drainage green roof substrate. In both cases, trays were planted in single species monocultures, plant type mixtures, and all species mixes. In the second experiment the small trays were watered through a rain simulator providing high and light rain. The findings of both experiments showed that plant diversity does not reduce water runoff, and that it is necessary to create green roof communities containing plant groups with different vegetation structures to maximise water absorption (Dunnett et al., 2008a).

Lundholm et al. (2010) designed a similar experiment to (Dunnett et al., 2008a) in Nova Scotia, Canada. They tested fifteen species of five different plant life-forms: creeping shrubs, creeping forbs, grasses, succulents and tall forbs to assess the impact of monocultures or groups of plants of one, three or five life-forms growing together during May to August of 2009. The aim of this experiment was to study whether the forms of the plants have any impact on different functions of the roof, in this case cooling and water runoff. Their findings showed that, in general, vegetated plots reduce temperature by around 10°C in comparison with un-vegetated bare substrate plots. The three and five live-form group treatments had around a 1.5°C greater reduction in temperature in comparison with the plots containing only one life-form. Nevertheless, the monoculture groups of *Solidago bicolor* and *Sedum acre* still had reduced temperatures like the three and five life-form treatments. However for water capture, the treatment formed using three different species of grasses displayed better capture than the treatment with a single grass species alone (Lundholm et al., 2010).

In general, the authors recommended the use of a combination of succulents, tall forbs and grasses to achieve optimal cooling and water capture. To obtain a broader picture, it is necessary to study whether these life-form combinations have the same optimal results in conserving the heat inside the building during winter and in different climates. Similarly, within other group plants such as succulents we can find different forms, which could be exploited to obtain optimised services and enhanced intelligent planting.

Blanusa et al. (2013) studied the effect of broad leaf perennial plants in comparison with a mix of *Sedum* species, on the temperature of leaf surfaces, air temperatures surrounding plants and the ground surface temperature in a 200 mm deep substrate. The species *Stachys byzantina* had the lowest leaf surface temperature, lowest temperature of substrate below the plants canopy and also the lowest air temperature above the canopy when the substrate was wet. These results related to the higher transpiration of the broad leaves of *S. byzantina* and to the reflective hairs of the leaf surface. However, low albedo, *S. byzantina* does not have a very high drought tolerance and requires supplemental watering during dry episodes (Blanusa et al., 2013). In cities with hot and dry seasons, where water availability is reduced, watering green roofs to induce evapotranspiration may not be possible, and therefore evapotranspiration rates will be very low during these times. The use of trichomes or reflective waxes in highly drought tolerant species can help to decrease heat absorption of buildings during the driest times of the year, without having to add water to the roof.

1.5.2 Physiological plant traits

Plant selection based on specific traits can be very informative in assessing survival and performance. Plant traits can be used to find species for the roof environment in starkly different climates. Nagase and Dunnett (2013b) tested twenty-six species of geophytes on 50 and 100 mm substrate depth plots on a roof in Sheffield with and without *Sedum* ground cover. The geophytes were selected due to their capacity to store water in their underground organs, the early flowering characteristics of some of the species, and their low maintenance. The majority of the bulbs flowered from March to June. The deeper substrate significantly improved emergence, growth, vegetative reproduction and number of flowers, while the addition of *Sedum* cover did not affect any parameter in the majority of species. In this experiment eight geophyte species were reported as high potential species to use on green roofs: including *Iris bucharica, Muscari azureu, Narcissus cylamineous* "February Gold", and others. Here, the interaction of two different traits, storage organs and ground coverage, was explored to determine roof planting efficacy.

Another crucial physiologic trait of plant forms was individual succulence of leaves. Farrell et al. (2012) tested five succulent species with different degrees of leaf succulence; *Sedum pachyphyllum, S. clavatum* and *S. spurium, Carpobrotus modestus* and *Disphyma crassifolium* under two watering regimes: well-watered and droughted, and three different substrate compositions: scoria, roof tile and bottom ash substrate. The aim of the experiment was to explore the effect of leaf succulence and substrate composition on plant water use and survival across treatments. They found that leaf succulence did not have a direct positive relationship with survival, since species like *D. crassifolium* with highly succulent leaves had lower survival than *S. spurium* which has a lower degree of succulence. As explained by Farrell et al. (2012), it is not only succulence which is the mechanism behind the plants' survival, but the faculty of the plant to reallocate water from old into new functional leaves. In terms of survival, leaf succulence cannot be the only criteria to select plant species for green roofs, thrifty and low water use also enhance survival.

Farrell et al. (2013) tested 12 species of granite outcrop communities with three different life forms: monocots, herbs and shrubs. Plants from granite outcrops grow on shallow substrates and usually experience diurnal and seasonal extremes of water, which make them potentially suitable for green roofs. In comparison with *S. pachyphyllum* the outcrop species had 9.6 to 58.8 times higher rates of transpiration, and were able to survive drought periods as well. In this research Farrell et al. (2013) were able to find physiological traits responsible for the plasticity in water use of the granite outcrop communities, which included the degree of root, stem or leaf succulence, in monocots and herbs. Some of the most water use efficient species were *Athropodium milleflorum, Stypandra glauca, Dianella admixta, Lomandra longifolia* and *Isotoma axillaris*. Examples like this show the potential for the incorporation of ecophysiology tools in the plant selection for novel environments like green roofs. They make use of the plant adaptations to environments while are similar or analogous to the roofs, with performances suitable to the services we aim to provide with the green roofs.

1.5.3 Natural habitats and plant communities

The study of plant communities from habitats similar to the roof environment is another method for plant selection. As Dunnett and Kingsbury (2008) argue, the design of the green roof plant community assemblages can be regional, in an attempt to replicate natural communities, or artificial where plants from similar environments, but from very different provenances, are assembled to achieve certain objectives, such as longer flowering periods available for pollinators and/or for aesthetic values.

Lundholm (2006) borrowed the concept "habitat template" from the ecology context to explain the need to find analogous habitats to the roof in order to access potential species for the roof environment. In these cases, the analogous habitats are not necessarily native to the locality of the building. Some good examples of "habitat template" include are species from communities of calcareous grasslands (Choi, 2012), or species from natural rock outcrops, like natural limestone formations, which are adapted to shallow and low-nutrient soils (Lundholm et al., 2010). This species and can be tested on roofs within cities of different habitats or climates to those of the selected plants.

The design of artificial plant communities by selection based on phenology can also be employed to find one method to find plant species suitable for green roofs. An example of this kind of selection was performed by Nagase and Dunnett (2013a), who studied the stages of establishment of annual meadows on extensive green roofs in the UK. The advantages of these communities are manifold, including low management, low cost, low usage of fertilizers and herbicides, high likelihood of becoming biodiversity enhancers and their aesthetic qualities (Nagase and Dunnett, 2013a). The authors tested 22 annual species from different provenances at different densities. The authors found that, with ample rainfall, a low seed sowing density (2 g/m^2) improves seed germination rate. In contrast, dry environments require a higher number of seeds germinate at a higher sowing density (4 g/m^2), and therefore this rate is advisable. This experiment was run for only during one growing season, nevertheless a longer term experiment considering the self-seeding of the established species and observing the changes in the plant communities over time is advisable to determine whether annual plant communities can establish on the roof environment. It is important to observe that the regeneration of annual communities on the roofs will also depend on the work of pollinators, and therefore the knowledge of relationships between the selected plant species and the pollinators of the area will benefit the establishment of these communities.

1.5.4 Biodiversity and spontaneous vegetation

The incorporation of new species to the plant palette of the green roof, using, different life forms will by itself, improve biodiversity on the roof (Brenneisen, 2005, Cook-Patton and Bauerle, 2012). The establishment of spontaneous vegetation can also help improve biodiversity, but in some cases it can work to its detriment. Nevertheless, both plant species introduced intentionally or secondary colonizers can provide benefits for wild-life and green roofs can become the habitats of rare, vulnerable and endangered plant species. Some plant species can be specifically chosen and planted in order to provide habitat to certain animal species, and therefore be used to construct a basic ecosystem atop buildings.

1.5.4.1 Planting native species

One way to enhance biodiversity is by the use of native species on green roofs. In this way native flora displaced by urban expansion and local habitat loss are protected and, in cases were native pollinators can reach the roof, a new pollen and nectar source is provided. Monterusso et al. (2005) tested 18 native Michigan species in 100 mm depth substrates and three different drainage systems. Plants were watered during establishment, from day 1 to 36 for 15 minutes three times a day. For the whole second growing season, plants were watered once for 15 minutes every day, and no supplemented watering was provided during the third growing season. The native plants displayed optional growth when water was freely available, and in the third season there was minimum growth and high number of species died. Species like *Juncus effussus* were not successful on the roof, since this these species usually grow on marshes, wetlands or very moist soils (USDA, 2002), while some grasses required very deep system roofs (Monterusso et al., 2005). The success of native species depends not only on their native status; their success depends on the similarity of the habitat of the species to that of the roof.

1.5.4.2 Spontaneous vegetation

Observing the arrival at establishment of spontaneous vegetation occurring on roofs can be a useful tool and a method to target species that can grow on green roofs in specific localities. The colonization of green roofs by wind or animal dispersal is unavoidable, and the colonizing species will range from weeds to pioneer plants, to endangered species (Brenneisen, 2006, Dunnett et al., 2008b, Köhler, 2006, Nagase et al., 2013). In these cases, identification of the colonizer species, knowledge of their growth habits, such as the size of the plant, root systems, seed dispersal, aggressiveness, and interactions with fauna, are parameters which can be used to decide whether the species should be encouraged or weather it needs to be discarded from the roof.

Nagase et al. (2013) recorded the spontaneous weed phenology on a green roof in Rotherham, in plots with two planting densities and two growing media: 10 cm with gravel mulch and 20 cm without mulch. The authors found that the amount of colonising weeds was lower in cases of higher initial plant density, while in low planting density plots, the amount of weeds decreased when the percentage cover of the planting exceeded the 50%. The plots with gravel mulch also had a lower number of weeds (Nagase et al., 2013). In the case of very aggressive weeds, or invasive plants such as *Buddleja davidii* and unwanted tree seedlings, preventing them from arriving to the roofs, and timed weeding before they in turn set seed, is a much needed practice (Nagase et al., 2013). Their aggressiveness can reduce the biodiversity of the roof and, in the case of plants with very fibrous long root systems such as *Buddleja* spp. can damage the roof structure (Gedge et al., 2010).

In a highly successful case of spontaneous vegetation Brenneisen (2006) reports that a 90-year-old green roof in Wollishofen, Zurich, designed with the intention of cooling the building, became the habitat of 175 plant species. Some of the species included endangered orchids from the plant communities of the wet meadows of the surrounding areas such as *Orchis morio*, *O. latifolia*, and *O. militaris* (Breneisen 2006). The substrate of this roof was composed of 50 mm of sand and gravel as drainage and 150 to 200 mm of top soil obtained from the surrounding areas. The use of top soil, (especially locally sourced!) is not always possible, nevertheless in Switzerland it is becoming encouraged in order to provide the moisture and micoyrrhiza necessary to support the germination at growth of native orchid species (Schneider, 2013).

Madre et al. (2014) surveyed the colonizer species of 115 roofs in France. Building's substrate depth ranged from 2 to 60 cm, heights from ground level up to 25 m, ages of green roofs from 1 to 42 years, and different maintenance degrees were all investigated. The authors found that substrate depth was the greatest with major effect on plant diversity, community structure and functional composition of the green roofs. They found that of 176 colonizer species across all roofs, 85% were native. 122 colonizer species were present in at least two independent sites, 18 species had a legal protection status and 3 species were classified as invasive. From their surveys, the authors suggest the use of a typology of green roofs depending on the vegetation structure, based on a classification for the plant communities in the Paris region: **Muscinal stratum** consisting of a biological soil crust composed of bryophytes, lichens, fungi, and small herbaceous and succulents like *Sedum;* **herbaceous stratum** dominated by non-woody herbaceous plants and grasses with 1 m or more height; **arbustive stratum** with shrubs and young trees up to 7m; and **arboreous stratum** with 1 to 7 m high trees. The depth of the substrate is directly related with the type of vegetation structure. The advice of the authors for future roof installations is to design roofs with varying substrate depths in order to increase the species richness and vegetation structure of the roofs. Furthermore they strongly advise the planting of more native species to support the native wildlife (Madre et al., 2014).

Long-term observations on green roofs' colonizers can provide insights into the development, establishment, and succession of plant species in these new environments. Dunnett et al. (2008b) monitored an experiment with two substrate depths, 100 and 200 mm, over six years, to determine the interactions of the planted and the colonizing species. The colonizing species were of two kinds: ruderal species dispersed by wind, and species with bigger seeds which were dispersed by animals such as birds. It was found that at the 200 mm depth, the colonizing species had greater biomass while at the 100 mm depth a higher species-richness was observed. The colonizing species, according to the authors, were typical of spontaneous urban plant communities (Dunnett et al., 2008b).

Köhler (2006) performed a long term study on two sites in Berlin, the roofs of the Paul-Lincke-Ufer buildings and the roofs of the Ufa-Fabrik installed in the mid-1980s. The first complex was composed of roofs of different slopes and exposures. The substrate had a depth of 100 mm made up with expanded clay, sand and humus, and was planted with vegetated mats. The Ufa-Fabrik roofs had 100 mm substrate depth, made up with sandy garden soil and 10 % of expanded clay, and were planted with seeds native to the Alps which were watered during some years. Some of the species colonizing the Paul-Lincke-Ufer roofs were *Poa bulbosa* and a lichen *Cladonia coniocraea.* Annual and other colonizer species were more abundant in times when more water was available, such as *Trifolium arvense* and *Medicago lupulina.* The most abundant species on these roofs were *Allium* species. Over the course of the study a single roof of the complex would be home to a total amount of 55 vascular species, with the minimum of 8 and the maximum of 25 at only one time (Köhler, 2006). For the Ufa roofs it was more difficult to identify the colonizers since the complete initial list of the species sown was not recorded. Nevertheless, over 13 years of observation, one of the roofs of the complex become home of a total of 91 vascular species with the minimum of 22 and a maximum of 64 at only one time. Some of the species with greater persistence were *Anthyllnis vulneraria*, *Onobrychis montana*, and *Medicago sativa. Sedum* species became more dominant when the irrigation was stopped. However the Ufa roofs had a higher species richness, probably due the location of the complex in a greener area in the shade of mature trees. Tree seedlings and highly competitive weeds were removed from the roofs.

Köhler and Poll (2010) compared modern extensive green roofs with tar-paper-gravel green roofs and developed a vegetation quality index that takes into account the relative plant cover and species quantity. The authors found that the modern extensive roofs had higher vegetation quality than that of the tar-paper-gravel at the same depths, while 12 cm depth substrates are the recommended depth to achieve a high vegetation quality. The roof aspect had a significant effect on the plant coverage and composition. The North facing roofs had higher cover and dominance of *Allium schoenoprasum* and grasses in comparison with the South and East facing roofs with lower cover and *Sedum* dominance. The plant richness of any one site depends on exposure to solar radiation and water availability, both diurnally and throughout the year.

The various studies presented in this section illustrate that the methodologies for green roof plant selection are quite varied and sometimes targeted to perform specific ecosystem functions. Nevertheless, the plant richness and plant community structure of the roofs depends not only on the initial species planting list, but on the planting densities, on substrate source and composition, the location of the building and its surrounding plant species, aspect of the roof and each season's climatic conditions. The dynamics of plant communities' structure during the life of the green roofs are multifactorial. It appears that green roofs within the cities tend to be colonized by urban cosmopolitan flora, ruderals and weeds, while roofs outside the cities are more likely to be colonized by non-ruderal native species and, in some cases, even rare or endangered ones.

1.6 *Sedum* dominated green roofs

As seen in the previous section independently of the initial planting list, roofs with thinner substrates, lower water retention, and higher solar radiation tend to be dominated by small, drought tolerant species such as *Sedum.* The deeper the substrate, the more shading and higher water holding capacity it possessed and, the higher amount of species and vegetation structures the roofs can support. The majority of the studies described above encourage the use of heterogeneous substrate depths, varied substrate composition and spatially mixed substrate water holding capacity to increase the types of vegetation on the roof and, by default, the multi-functionality of the roofs. The above considerations of design in to new roofs can help to improve the cooling and energy saving capacity of the roof, ameliorate water runoff, and increase biodiversity and habitat for wild-life among other factors. Nevertheless, there are no studies for the improvement of the already installed *Sedum* green roofs and furthermore, extensive monoculture *Sedum* roofs continue to be installed and remain a popular low-cost and low maintenance for architects and planners.

Sedum species become dominant on extensive green roofs for several reasons. Firstly, the are often planted at high densities as they are an economical option on newly-laid substrates. But the main factor in their ecological dominance as well as historical dominance in green roof industry is that they can grow very successfully on the harsh environment of the roof. *Sedums* can grow in shallow substrates, can withstand droughts and still provide a rapid cover to the roof. Nevertheless, *Sedum* dominated roofs, are usually composed of one or very few similar species. And, as seen, these monocultures or species-poor assemblages do not maximise the services that the roof could provide: due to their short flowering period; homogeneous surface textures and low evapotranspiration rates. Even with all these well-known draw-backs and constraints many examples of recently installed extensive *Sedum* roofs around the world. These include the 2014 Jacob K. Javits Convention Center in New York City where vegetative mats of *Sedum* were installed on top of more than 27,000 m^2 of roof top (Greenroofs.com, 2014a). In 2013, the BTS-2 roof in Bogota, Colombia, a 245 m^2 *Sedum* roof was installed (Greenroofs.com, 2013). In the UK, examples of extensive *Sedum* green roofs include the Sedum House in Doncaster, South Yorkshire (Greenroofs.com, 2014b) ,and the *Sedum* roof on top of the Lillie Road development (Greenroofs.com, 2003).

Figure 1.6.1 Jacob K. Javits Convention Center in New York City (reference)

In Mexico City, the majority of green roofs are *Sedum* roofs. Nevertheless the native Mexican *Sedum* species used in these systems are far taller than the species used in the European and the US systems. In spite of this, only three main Mexican *Sedum* species are used, *S. griseum, S. prealtum* and *S. moranense.* In the Mexican case of green roof design, this is a strange phenomenon since the biodiversity of not only *Sedum* species, but the whole Mexican Crassulaceae family, to which *Sedum* belong is very high and for this reason a much wider plant palette can be developed from the native species available.

Clearly the market for *Sedum* for green roof use will continue, but often the ‘green roof’ has become synonymous with the ‘*Sedum roof’* and this has resulted in a backlash against the genus by several green roof proponents (Gedge, 2014). To address the concerns of this anti-*Sedum* movement it is perhaps necessary to confront the issue in several ways: by identify new plant material that can perform similar functions as existing *Sedum* ground cover species, and by the same token, defend the further view of *Sedum* and the Crassulaceae family on new and old green roofs by taking advantage of their full potential

Figure 1.6.2 Green roof in roof of high school *Felipe Carrillo Puerto* in Mexico City with *Sedum dendroideum, S. griseum* and *S. moranense.*

Figure 1.6.3 Green roof in Centro Comercial Iztapalapa in Mexico City with *Sedum prealtum* , *S. griseum, S. moranense, Agave americana* var. *variegata,* and exotics *Aloe asperola* and *Portulaca afra.*

Figure 1.6.4 Green roof in the HSBC headquarters in Mexico City with *S. prealtum, S. griseum, S. moranense, Agave americana* var. *variegated, Agave tequiliana* and exotic *Delosperma cooperi.*

As shown, it is evident that a very high number of square meters of *Sedum* roofs continue to be installed across the world, but there is, as yet, no published research in how to improve these monoculture systems. This is primarily because the majority of current investigations concern the improvement of services, and usually address this by using deeper and more heterogeneous substrates. In order to find suitable species that can survive the normally shallow, high drainage substrates of *Sedum* roofs, perhaps we have to observe more closely the *Sedum* genus and its family, Crassulaceae, with the aim to improve the current texture, colour and flowering architecture of the *Sedum*. One of the approaches to find different forms of Crassulaceae species is to look to the centres of biodiversity of the Crassulaceae family such as southern Africa, China and in particular Mexico (Meyrán-García, 2003, Stephenson, 1994).

1.7 The Mexican Crassulaceae

This research focused on the Mexican species of the Crassulaceae family as a source of underexplored and unexploited green roof plants. Mexico holds a great biodiversity of Crassulaceae species, nevertheless this does not imply that all Mexican Crassulaceae species have the adaptations required to grow on green roofs in their native area, or in green roofs of other climates. Species such as *Echeveria calycosa,* for example, which grows in shaded rocky river banks in pine forests of Michoacan, cannot withstand prolonged periods of drought (Pilbeam, 2008). Or species like *Echeveria setosa* from Oaxaca which grows in shaded areas cannot tolerate high solar radiation (Pilbeam, 2008). In Mexico, the Crassulaceae species are distributed throughout the whole country in many different terrains and habitats and across a high range of altitudes (Clausen, 1959, Evans, 1983, Meyrán-García, 2003, Pilbeam, 2008). Their wide altitude distribution implies that the Mexican Crassulaceae species can also grow across a high climatic range. This extraordinarily high diversity means that if Mexican Crassulaceae species are to be successfully incorporated into green roofs across different climates, it is necessary to develop a plant selection methodology to identify species suitable for green roofs in specific climates.

1.8 Selecting plant species using world climatic classifications

In the literature review of the different plant selection methodologies that have been previously used, it was seen that all the current methodologies have been designed to look for species in a particular place. Even though this is a logical and desirable strategy a plant selection methodology aim at synthesising general shared climatic parameters can bring several benefits, especially in a world undergoing anthropologically-induced climatic change. With climate change, plant species that prove successful in one area, might not survive tomorrow in the same location (Walther et al., 2002). The use of a world general climatic classification can help to characterize plant species ecotypes for specific climates. This not only will work in terms of survival and growth, but perhaps could be extrapolated in to some environmental services such as cooling and water runoff. The incorporation of climatic classification systems such as the Köppen-Geiger-Kottek into our plant selection for green roof design can help us to adapt faster to climatic changes.

1.8.1 The Köppen-Geiger-Kottek classification

The Köppen classification map of the world climates was introduced for the first time by Wladimir Köppen in 1900 and revisions of this map were incorporated by Geiger in 1954 and 1957 (Kottek et al., 2006). The last update for the map was published by Kottek et al. (2006). The Köppen classification uses three letters to denote the climates. The first capital letter refers to zones classified considering plant groups as climatic indicators where (A) is equatorial zone, (B) arid zone, (C) warm temperate zone, (D) snow zone and (E) polar zone. The second letter refers to precipitation, and the third letter indicates air temperature (Kottek et al., 2006). The actualized Köppen-Geiger-Kottek map was updated with global data of precipitation and temperatures over a fifty year period 1951-2000, and has a higher resolution that permits greater regional details to be factored in (Kottek et al., 2006). The map indicators of climate, precipitation, and temperature can be a very useful tool to locate regions similar to that of the roof, and that can contain potential species for these new urban environments. For this reason, the present study will exploit the Köppen-Geiger-Kottek system to determine its efficacy as part of a plant selection methodology. Two case studies, in two different climates, were selected: **Cwb** (**warm temperate, dry winter and warm summer**) and **Cfb** (**warm temperate, fully humid, and warm summer)** the climates of Mexico City and Sheffield, UK respectively.

1.9 Overall aim of the research

To develop a plant selection methodology to identify candidate Mexican Crassulaceae species for extensive green roofs in different climates **Cwb** (**warm temperate, dry winter and warm summer**) for Mexico City and **Cfb** (**warm temperate, fully humid, and warm summer)** for Sheffield.

1.9.1 Research questions

- Is it possible to develop a plant selection methodology to target Mexican Crassulaceae species for different climates?
- Which parameters should be considered in the plant selection methodology?
- Can the selected Mexican Crassulaceae species survive and grow in the climates they were targeted for: **Cfb** (**warm temperate, fully humid, and warm summer) Cwb** (**warm temperate, dry winter and warm summer**)?
- Can Mexican Crassulaceae species improve extensive green roofs dominated by ground cover *Sedum*?

1.9.2 Research objectives

The objectives of this research are:

To design a plant selection methodology for specific climates in accordance with the Köppen-Geiger-Kottek map of world climate classification.

To investigate which is the best season to plant cuttings in green roofs in **Cwb** (warm temperate, **dry winter** and warm summer) climates.

To investigate the minimum depth for Mexican Crassulaceae species to obtain optimal performance in roofs in **Cwb** (warm temperate, **dry winter** and warm summer) climate.

To investigate which Mexican species of the Crassulaceae family can have an optimal performance in the **Cwb** (warm temperate**, dry winter** and warm summer) climate.

To investigate which Mexican Crassulaceae species have the best performance in **Cfb** (warm temperate, **fully humid**, and warm summer**)** climate

To investigate whether Mexican Crassulaceae species can grow together in with native *Sedums* in extensive *Sedum* green roofs in **Cfb** (warm temperate, **fully humid**, and warm summer**)** climate.

The following chapter of this study will present the development of a plant selection methodology based on the Köppen-Geiger-Kottek map of world climate classification. This is followed in Chapter 3 and Chapter 4, with methodologies and results of experiments which test the selected Crassulaceae Mexican plant species for (**Cwb**) climate. Chapter 5 presents the methods and results of experiments testing the selected Crassulaceae Mexican plant species for (**Cfb**) climates. Finally Chapter 6 will present the overall conclusions to this research, and discuss further lines of investigation.

Chapter 2 Plant selection of Mexican Crassulaceae

2.1 Introduction

This chapter is divided in two main sections. The first presents the general characteristics of the Mexican Crassulaceae species, generalities about the family, their habitat, distribution and uses on green roofs. The second section presents the methodology for the Mexican Crassulaceae plant selection developed and tested in this research. This methodology is a system combining several layers of information to identify geographical areas that might have potential species suitable for the specific conditions of two distinct roof settings for the study: namely, one in a warm temperate environment with dry winter and warm summer climate (Cwb) and another roof in a warm temperate environment with a fully humid warm summer climate (Cfb). Briefly, the methodology comprises the general Köppen-Geiger-Kottek climate classification of the geographical region under consideration for plant selection, the characterisation of the climate at the green roof's location; and the overlaying of the two zones. This method is applied specifically to the physiographic provinces of Mexico, and therefore an analysis of the types of vegetation present in these zones that might hold potential species for the specific roofs is undertaken. Finally the chapter presents the two final lists containing the species identified from the selection methodology to test in the in Mexico City (Cwb), and in the UK (Cfb).

2.2 The Crassulaceae family

2.2.1 General characteristics

The Crassulaceae family is a world-distributed group of plants with 34 genera and 1,410 species with the centres of diversity in Mexico and South Africa (Thiede and Eggli, 2007). The most evident characteristics of the family are their succulent leaves, sometimes stems and underground roots, or in a lower degree base of the stems, (Eggli, 2003). Succulence is a morphologic adaptation usually found in plants from arid zones as a device to store water and to resist drought. Crassulaceae species are often found in zones with low precipitation and/or soils with rapid drainage (Meyrán-García, 2003, Stephenson, 1994).

2.2.2 The Mexican Crassulaceae within the Crassulaceae Family

The family Crassulaceae has been restructured by taxonomists many times. It is divided into subfamilies, tribes and clades. In the most recent classification it has been divided into three subfamilies: Crassuloideae, Sempervivoideae and Kalanchoideae; all three with xerophyte species (Thiede and Eggli, 2007). The subfamily Crassuloideae is mainly distributed in southern Africa, Kalanchoideae in Africa and southern Asia, and Sempervivoideae represented mainly in the northern hemisphere (Thiede and Eggli, 2007). The Mexican Crassulaceae species belong to the subfamily Sempervivoideae, tribe Sedeae. This includes the genera *Echeveria,* *Graptopetalum, Lenophyllum, Pachyphytum, Villadia* and *Thompsonella* which are part of the clade *Acre*, while the genus *Dudleya* belongs to the Leucosedum clade.

The genus *Echeveria* is further divided into 17 Series depending on their inflorescence disposition, size of stem, and growth form : 1) Echeveria, 2) Nudae, 3) Spicatae, 4) Racemosae, 5) Mucronatae, 6) Ciliatae, 7) Paniculatae, 8) Urbiniae, 9) Longistylae, 10) Valvatae, 11) Secundae, 12) Chloranthae, 13) Pruinosae, 14) Angulatae, 15) Occidentalis, 16) Thyriflorae, and 17) Gibbiflorae (Pilbeam, 2008). The genus *Sedum* is divided into two subgenera *Sedum* and *Gormania* (Eggli, 2003). The difficulties in classifying the Crassulaceae family mean that the present classification will probably be altered again. It is also testimony to the high diversity of the Mexican Crassulaceae family.

2.2.2.1 General morphology

Crassulaceae growth form ranges from herbs, subshrubs to shrubs, and a few with tree-like growth up to 8-10 m high, and a few aquatics, epiphytes or scandent plants, i.e. with a creeping habit. The majority are perennials, but some are annuals, biannual and monocarpic, where the plant dies after its first and only inflorescence (Eggli, 2003, Meyrán-García, 2003). During frost or drought, most perennials usually keep the shoots and some leaves to survive, nevertheless some species are deciduous, and these plants generally have succulent or tuber like stems that perform photosynthesis. Rhizomes are sympodial (i.e. present a lateral growth), with the exception of the *Rhodiola* genus, and roots are generally fibrous and occasionally thick and tuberous. Adventitious roots are easily formed in various forms of shoots when there is high air humidity. Mycorrhizal symbiosis has been seen within the roots of *Sempervivum* and *Sedum,* but there is currently little known about it (Thiede and Eggli, 2007, Eggli, 2003).

The adult leaves are usually simple and in a few occasions compound with pinnate, lobed, laciniate or with a shield form. The leaves are usually flat to subulate, regularly flat on the front and semi-elongated and cylindrical on the back, or fully elongated and cylindrical leaves with pencil shape, sometimes with a keel. The surface of the leaves can be glabrous, glaucous or tomentose. Margins are often entire or with teeth, and on occasion ciliated (i.e. with hairs). Leaves can easily fall and grow adventitious roots and shoots (Meyrán-García, 2003, Thiede and Eggli, 2007). The arrangement of the leaves is usually scattered (i.e. alternate) and spiral or in opposite pairs and a few sedums are whorled. There are a large number of species that form rosettes with their leaves; in these cases the rosettes can be with stem or stem-less, or can be terminal. The rosette shape helps to create a buffering microenvironment to modulate temperature fluctuations and produce a higher humidity from the rest of the aboveground environment by increasing the boundary layer, which helps the plants to survive in extreme environments (Körner, 2003, Martorell and Ezcurra, 2002). In some cases the rosettes can grow from a stolon and grow adventitious roots as a means of vegetative propagation (Stephenson, 1994, Thiede and Eggli, 2007). All the above features are highly advantageous characteristics to survive in very exposed places with shallow soils (see 1.6).

Sexual Reproduction in the Crassulaceae

The inflorescences of species from the Crassulaceae family are generally lateral or terminal with spikes or panicles with many flowers, and very rarely with only few and/or axillary flowers (Thiede and Eggli, 2007). Flowers are bisexual or unisexual and usually with radial symmetry. They can have 3 to 32 parts, but usually 5 and the stamens ripen before the stigmas become receptive (Eggli, 1993, Eggli, 2003, Thiede and Eggli, 2007). Sepals are free or basally united like the petals, which sometimes form a corolla tube that can be either short or long. The number of stamens is usually as many or double as the number of petals, and can be free or fused to the petals. The filaments are free or sometimes form tubular corolla (Eggli, 2003, Thiede and Eggli, 2007). Ovaries are usually superior to semi-inferior (with exception of *Rhodiola*), and therefore seed production is developed above the line of emergence of petals. The number of carpels is the same as petals; they can be completely free or almost free with or without stalk (Eggli, 2003, Eggli, 1993, Thiede and Eggli, 2007).

Vegetative reproduction

Some plant families have developed vegetative reproduction, such as the production of plantlets on detached leaves. It is thought that this form of vegetative reproduction is a response to the low percentage of seed and seedling survival in shallow and rocky soils or dry environments where the plants grow (Gravatt and Taylor, 2004). In the Crassulaceae family many species from *Echeveria, Pachyphytum, Graptopetalum, Sedum, Crassula,* and other genera, develop plantlets from detached leaves which fall on the ground (Gravatt and Taylor, 2004). Species like *Kalanchoë daigremontiana* have the ability to develop plantlets in the margin of their leaves whilst still attached to the mother plant, a strategy known as constitutive plantlet-forming (Garces et al., 2007). Another form of vegetative reproduction, is by offsets that can grow on the base of the plant or at the end of long stolons to form a mat (Meyrán-García, 2003, Thiede and Eggli, 2007).

Benefits of vegetative reproduction in Crassulaceae species can be found in the reproductive process of detached leaves of *Sedum wrightii*. The detached leaves of this regular CAM plant had 78% success in rooting after 7 weeks. The water content on day 0 was 98% and by day 120 the leaves still contained 89%. The malic acid accumulation in the leaves by day 120 had declined 36% from day 0 content, but its presence indicated that the leaves were still physiologically active, and probably providing photosynthates directly to the plantlet (Gravatt, 2003). The major benefit of vegetative reproduction is that allows Crassulaceae species to reproduce in environments and seasons that are not adequate for sexual reproduction. All forms of vegetative reproduction in species of the Crassulaceae family can be advantageous in green roof systems, since they permit a fast propagation of the plant in the shallow and dry substrates of the roof. Furthermore, they do not require immediate and constant humidity for successful establishment, unlike germinating seeds.

Process of leaf vegetative reproduction

Gravatt and Taylor (2004) compared the vegetative reproduction in detached leaves of *Sedum wrightii* on a moist vermiculite versus a dry environment. The process starts with the formation of a callus at 48 to 60 hours at the base of the leaf. By the second to third day, a small protuberance starts to develop in the leaf. Young shoots emerge from callus tissue after 5 to 7 days with two primordial leaves. The first roots appear on the leaf around day eight (Gravatt and Taylor, 2004). Detached leaves of *Sedum stahlii* in a moist chamber took longer to develop callus tissue than in a dry environment. In humid conditions *Sedum stahlii* showed the same results as *S. wrightii*, but in dry conditions the roots were formed before the emergence of the young shoot (Yarbrough, 1936). Species differences in Crassulaceae vegetative reproduction may be strong determinants of green roof planting success and survival responses will differ with climate and season.

2.2.2.2 Physiological adaptation

As for most succulent plants, Crassulaceae species have their parenchyma cells composed of large vacuoles where the plant stores water (Rost, 1969). A s part of their vegetative anatomy, Crassulaceae epidermis generally possess thick cuticles that prevent loss of water by transpiration, leaf damage and/or breaking by wilting. Some species present glossy cuticles, trichomes or wax to reflect excess light, reduce heat stress on leaves and protect from wind, frost and pathogens. Often the leaves are reduced in surface area to prevent water loss (Smith et al., 2010, Larcher, 1995, Evans, 1983). A critical adaptation of many species from the Crassulaceae family is Crassualcean Acid Metabolism (CAM) photosynthesis, a metabolic pathway that prevents water loss from transpiration (Stephenson, 1994).

CAM photosynthesis

Crassulacean acid metabolism, or CAM photosynthesis, is a pathway found in many xerophytes used to prevent loss of water during CO_2 fixation. CAM can be found in aquatic plants as well, like *Isoetes* spp. but in these cases CAM photosynthesis helps with the CO_2 intake through the roots. Several epiphytic and lithophytic ferns also perform CAM (Lüttge, 2004). In fact, it is known that CAM can be found in around 6% of the higher plant species, distributed in 33 families and 328 genera (Smith and Winter, 1996). The families that hold most CAM species are the Orchidaceae, Bromiliaceae, Clusiaceae, Liliaceae, Crassulaceae, Cactaceae and subfamily Agavaceae (Lüttge, 2004, Smith and Winter, 1996). Due to the appearance of CAM in different families with no recently shared ancestry, it is thought that the pathway evolved polyphyletically, this is that CAM evolved through different lines at different periods during the evolution of the plant kingdom (Lüttge, 2004).

Morphotypes of CAM plants

Through the wide range of species that perform CAM, the only morphological or anatomical feature common to all, in a higher or lower degree, is their **succulence**. In plants with succulent leaves, such as Crassulaceae species, this is due partly to the large central vacuoles of the cells used for the accumulation of organic acid during the night and to the tissue in charge of water storing (Lüttge, 2004). It is this succulence that is largely responsible for their high tolerance to water deficit.

CAM vs C_4 and C_3 photosynthesis

Usually plants assimilate CO_2 during the day through C_3 photosynthesis with the use of RuBisCo (ribulose-1,5-bisphosphate carboxylase/oxygenase). When the leaf temperature increases RuBisCo enzyme becomes inefficient and tends to fix O_2 instead of CO_2 (Ehleringer et al., 1991). This leads to photorespiration in which CO_2 is released. To achieve a highly efficient CO_2 uptake, plants have developed two different pathways from C_3: CAM (crassulacean acid metabolism) and C_4 photosynthesis, both forms saturate RuBisCo with high concentrations of CO_2 and block the oxygenase reaction (Cushman and Bohnert, 1997, Ehleringer et al., 1991, Smith et al., 2010). These two alternatives use phosphoenolpyruvate carboxylase enzyme (PEPC) to capture CO_2 in the form of an organic acid and two carboxylation reactions. The main difference between C_4 and CAM is that C_4 separates the two carboxylations spatially, while CAM does it temporarily, between night and day (Cushman and Bohnert, 1997, Lüttge, 2004).

In C_4 photosynthesis the two carboxylations for the concentration of CO_2 are usually performed in the mesophyll and in the bundle-sheath cells, a structure proper of C_4 plants known as Kranz anatomy (Ehleringer et al., 1991, Smith et al., 2010). The mesophyll (outer cells) and bundle-sheath (inner cells) layers are arranged in ring-shape around the vascular bundles. Both layers contain chloroplasts but in the mesophyll no RuBisCo is present, instead PEPC captures CO_2 in the form of a four carbon organic acid. This organic acid is transported to the bundle-sheath where it is decarboxylated, the resulting CO_2 surrounds the RuBisCo and the normal C_3 pathway continues (Ehleringer et al., 1991).

CAM pathway

The CAM pathway can be described in four stages (Osmond, 1978). Phase I is performed during the night with open stomata. In this phase the enzyme phosphoenolpyruvate carboxylase

(PEPC), stored in the intracellular fluid (cytoplasm), captures CO_2 and produces oxaloacetate. The oxaloacetate is reduced to malate and stored in the cells' vacuoles. Phase II occurs during the early hours of the morning. At this point stomata are still slightly open and CO_2 is obtained through normal RuBisCo assimilation (Cushman, 2001, Osmond, 1978).

During phase III, in full daylight with closed stomata, malate is decarboxylated through one or three carboxylases (enzymes) that can be used together or separately (NADP-ME, NAD-ME and/or PEPCK) depending on the species (Dodd et al., 2002). The products obtained by the decarboxylation are CO_2 and pyruvate. The CO_2 is then absorbed by the chloroplast with the use of RuBisCo and generates carbohydrates in the conventional photosynthetic way. One part of the sugar is used for growth while the other part is used to form PEPC by glycolysis and used again, for night CO_2 fixation (Dodd et al., 2002). Phase IV corresponds to the end of the day, when a minimal amount of CO_2 is obtained again through normal RuBisCo assimilation, with stomata open, before the PEPC enzyme starts to produce malate at night and phase I starts again (Osmond, 1978, Cushman, 2001).

Constitutive, Facultative, Idling and Cycling CAM

The generic CAM pathway as described above can present different adjustments depending on species. Depending on the use of CAM is possible to distinguish between constitutive and facultative CAM (Winter et al., 2008). Crassulaceae species like *Kalanchoë daigremontiana* or Cacti like *Opuntia basilaris* are known for being constitutive CAM. This means that during their whole mature life they perform regular CAM photosynthesis no matter the availability of water (Osmond, 1978, Sipes and Ting, 1985, Winter et al., 2008). It has been observed that constitutive CAM plants usually develop the pathway in mature leaves, and leaves of young plants only perform C_3 photosynthesis. In these cases once the leaves of the plant achieve maturity the CAM pathway is not reversible (Gehrig et al., 2005).

Other CAM species are facultative, like *Clusia pratensis.* This species performs C_3 photosynthesis and changes to regular CAM under stressed conditions, such as high salt content or drought, but when water is available reverses to C_3 photosynthesis (Gehrig et al., 2005). Nevertheless this distinction has to be taken carefully since there is a wide spectrum of possibilities of the expression of CAM, from fully controlled by the age of the plant to fully controlled by changes in the environment (Winter et al., 2008).

Examples of other expressions of CAM are CAM-Idling and CAM-Cycling. During extreme drought some CAM plants change in to CAM-Idling where CO_2 is recycled internally to perpetuate the organic acid cycle and stomata remain fully closed day and night so there is no gas exchange; once water is available plants go back to normal CAM (Cushman and Bohnert, 1997, Ehleringer et al., 1991, Lüttge, 2004, Sipes and Ting, 1985). CAM-cycling is another form of CAM in which plants such as *Pereskia* perform 100% C_3 gas exchange and have organic acid fluctuations during the day, but no CO_2 fixation at night. When plant species that perform CAM-cycling experience drought, they change in to CAM or CAM-idling (Ting, 1985)

Crassulaceae family and CAM photosynthesis

Even though CAM metabolism is named after its expression in Crassulacean species, not all plants belonging to this family perform constitutive CAM, in fact, several different photosynthetic pathways can be found in the family (Gravatt and Martin, 1992). Species like *Sedum acre* collected from the field in Germany showed C_3 photosynthesis *in situ* and after drought treatment in the lab it switches to the CAM pathway (Kluge, 1977). In well-watered conditions *Sedum integrifolium* (from moist meadows at Mt. Evans, Colorado at 3900 m) and *Sedum ternatum* (from sandy soil of river bank in Chatman, North Carolina at 120 m) showed C_3 photosynthesis and no malic acid fluctuations. *Sedum telephioides* (from granite cliff in Caldwell, North Carolina at 1040 m) and *Sedum nuttallianum* (from limestone rock in Newton, Missouri at 365 m) show C_3 gas exchange and malic acid fluctuations indicative of CAM-cycling. In the same treatment *Sedum wrightii* (from a semi-desert of Texas) presented regular CAM (Gravatt and Martin, 1992). With less frequent watering *S. integrifolium* and *S. ternatum* change to CAM-cycling, *S. telephioides* and *S. ternatum* perform at the same time CAM-cycling and a low level regular CAM, while *S. wrightii* stayed with regular CAM (Gravatt and Martin, 1992).Clearly these metabolic limitations and flexibilities have major implications for species responses on green roofs in different climates.

Several Mexican species have been tested in respect to their CAM performance. Nine species of *Echeveria* (*E. agavoides*, *E. halbingeri* var. *sanchez-mejoradae*, *E. bifida*, *E. simulans*, *E. affinis*, *E. dactylifera*, *E. secunda*, *E. pulidonis*, *E. longissima*, *E. leucotricha*), two species of *Pachyphytum* (*P. bracteosum* and *P. glutinicaule*) and *Graptopetalum amethystinum* showed in situ a regular CAM fixation. When subjected to non-water-limited greenhouse treatments all species showed the same regular CAM fixation with no switch towards a weak CAM or C_3 photosynthesis (Rundel et al., 1979).This experiment exemplifies how many Mexican species exhibit constitutive CAM- clearly an important factor to be considered when interpreting plant responses to green roof experiments.

2.2.2.3 General description of Mexican Crassulaceae Habitat

The Mexican species of the Crassulaceae family grow in a wide variety of ecosystems: from dry xerophyte scrubs to humid cloud forests and from hot tropical deciduous to temperate conifer forests (Clausen, 1959, Evans, 1983, Meyrán-García, 2003, Pilbeam, 2008, Rzedowski, 1986, Stephenson, 1994). Nevertheless, what most of the species have in common is their selection for particular microclimates within these ecosystems. Crassulaceae stress tolerant species thrive better in areas with low competition (Stephenson, 1994), therefore the habitats they select will usually be confined to cliffs, rocky steep slopes, crevices or cracks of rocks, and tree branches of cacti or agave for the epiphytes or arid plateaus (Evans, 1962, Meyrán-García, 2003, Stephenson, 1994). These habitats are not necessarily poor in nutrients sometimes the shallow soils on the rocks can contain large quantities of nutrients from the decomposition of mosses, lichens and other bryophytes (Clausen, 1959).

In accordance to their wide distribution among different ecosystems, the annual precipitation experienced by the Mexican Crassulaceae species ranges from extreme arid to 200 mm to 1600 mm a year (Evans, 1983). Rain is usually distributed during the summer and little or no precipitation occurs during the winter, with the exception of the North West of Baja California, which does have precipitation during the winter season (Evans, 1983, Rzedowski, 1986). Nonetheless in areas with high precipitation plants are usually found growing on walls and rocks with high porosity and rapid drainage. Some examples are the species surrounding the volcano Cofre de Perote in Veracruz, which grow on igneous soils cliffs, or species of the Sierra Madre Oriental on sedimentary soils from areas of limestone and sandstone (Meyrán-García, 2003). Consequently, even in zones with high annual precipitation this type of vegetation struggles to obtain water. Wind and sun exposure varies depending on whether the plant habit is to grow in exposed places, such as walls or alpine sites, or whether it is secluded in the lower areas of ravines or protected within rock cracks, or whether they grow on north or south facing sites. Adaptations to these changes of their environments therefore we can be seen in the quantity of trichomes or wax on their leaves (Evans, 1983, Meyrán and López, 2003), among other traits, and these species differences will determine suitability for different green roof environments.

2.2.2.4 Distribution of the Crassulaceae family in the North and South America by genera

As mentioned before, the North American and South American continents hold Crassulaceae genera unique to the land mass such as *Echeveria, Graptopetalum, Lenophyllum, Pachyphytum, Thompsonella, Villadia* and *Dudleya*, and a diverse representation of the cosmopolite genus *Sedum*. This section will present a short summary of the distribution of the genera throughout the American continents and, more specifically, in Mexico.

Dudleya

The species of this genus are mainly distributed in the southwest coast of the USA with some species in Arizona and possibly Nevada (Low, 2008). In Mexico the genus *Dudleya* is distributed in the peninsula of Baja California in the states of Baja California Norte and Baja California Sur. There have not yet been records of *Dudleya* species further south, inland, on the main land. Most of the *Dudleya* species grow in coastal regions and very few grow in the mountains of Baja California Norte and Sur (Low, 2008). *Dudleya* species usually grow on vertical shaded cliff walls, in very shallow soils (Low, 2008).

Echeveria

The genus *Echeveria* has around 200 species distributed in the southern USA, Mexico, Guatemala, Honduras, Nicaragua, Costa Rica, Panama, Colombia, Ecuador, Venezuela, Peru, Bolivia, and northern Argentina although the majority of species are found in Mexico (Pilbeam, 2008). In Mexico, most species grow in the south of the country, with the state of Oaxaca as the epicentre from where the distribution expands into the rest of the country. In the USA the only species growing is *E. strictiflora*, which is found in Texas (Low, 2007a, Pilbeam, 2008). A small number of epiphytic species are found in Central America. Species from Series Nudae grow from the south of Mexico down to Ecuador. Species from the Series Racemosae grow from southeast Mexico, in Central America and from Colombia to Peru with eleven species. Three taxa are known in Bolivia and one in Argentina (Pilbeam, 2008).

Graptopetalum

The *Graptopetalum* genus is formed of 20 species (Etter and Kristen, 1997). The majority of the species are distributed in the Northwest of Mexico in the states of Sonora, Chihuahua, Sinaloa, Durango, with some species towards the Southwest Nayarit, Colima and Jalisco and other species in Zacatecas, Guanajuato, Tamaulipas, and Veracruz (Etter and Kristen, 1997).

Pachyphytum

The Pachyphytum genus has 20 species that are distributed mainly in the centre of Mexico. The state Hidalgo has the highest number of Pachyphytum spices (five) and the rest of the species are distributed in Guanajuato, San Luis Potosí, Querétaro and Jalisco, with very few species in Oaxaca, Michoacán and Tamaulipas.

Sedum

The genus *Sedum* is formed of approximately 420 species. It is the largest genus of the Crassulaceae family (Eggli, 2003). It is distributed mainly in the North American continent with around 170 species, 30 distributed between Canada and the USA and about 120 species native to Mexico and 20 species distributed in Central and South America (Eggli, 2003) . In Mexico a large number of species of *Sedum* are native to the Mexican Transverse Volcanic Belt, a range of mountains and volcanoes that crosses Mexico from the West around Jalisco state to the East reaching the coast of Veracruz (Evans, 1983). Many species are also from the states of Oaxaca and San Luis Potosí. The rest of the species are distributed through the Sierra Madre Oriental and the Sierra Madre Occidental and the Mexican Plateau: two important mountain ranges and a plain that will be further described in Chapter II (Evans, 1983).

Villadia

The genus Villadia was erected 1902 by a botanist J. N. Rose, together with *Altamiranoa*, since the description of *Sedum* made by Linnaeus would not have allowed the introduction of several Mexican species due to their joint petals (Low, 2007c). The genus has been removed and reintroduced and at the moment holds around 24 species distributed from the southern USA to Peru with the biggest distribution in Mexico (Eggli, 2003, Low, 2007c).

2.2.3 Conservation status of the Mexican Crassulaceae species

Mexican Crassulaceae species populations are usually small and sometimes only localized in single locations, a factor which puts a great pressure on the conservation of certain species. In the NOM-059-SEMARNAT-2010 a document which lists Mexican flora and fauna species at risk, 18 Crassulaceae species are mentioned, of which 11 are under danger of extinction, 5 are under special protection and 2 are threatened (SEMARNAT, 2010). Nevertheless, botanists and experts of the family such as the Curator of the National Crassulaceae Collection in Mexico, suggest that more species are threatened primarily from the uncontrollable expansion of cities and fast urbanization of rural areas (Reyes-Santiago, 2010).

In order to counteract the loss of flora the Mexican Strategy for Plant Conservation 2012-2030 (MSPC) has a mission to increase and integrate the knowledge of Mexican plant species, and work towards its conservation and sustainable use (CONABIO, 2012). Some of the goals of the MSPC is to **conserve plant species *ex situ* in an effective and attainable manner, to give a directive towards the change of attitude in the society, and to contribute to the conservation and sustainable use of plant resources** (CONABIO, 2012). In relation to these goals, green roofs can become designated spaces for *ex situ* conservation of Mexican Crassulaceae as well as a space for public awareness. Furthermore, by choosing one's Crassulaceae species based on a roof's physiographic zone, the green roofs can become refugee and seeding sites for the repopulation of the surrounding environs.

2.2.4 The use of Mexican Crassulaceae species on green roofs

The most commonly used slow-growth plants in green roofs are *Sedum* species from the Crassulaceae family. Many Crassulaceae species, share with the *Sedum* genus physiological adaptations to drought, shallow substrates and highly exposed environments. Nevertheless *Sedum* species are considered to have minor aesthetic value because of their inconspicuous flowers, lack of texture and structure and homogenous colour. In terms of biodiversity these same characteristics are a disadvantage (Dunnett and Nolan, 2004), while in very hot places they do not improve the cooling of buildings due to their low transpiration (Wolf and Lundholm, 2008, Nagase and Dunnett, 2010, Farrell et al., 2012, Farrell et al., 2013). Nonetheless Mexican Crassulaceae species can bring some refreshment to the *Sedum* palette, especially on roofs that do not only look for the cooling effect of green roofs. It is still advisable to have rich biodiversity roofs with much more than one single family, but in cases when *Sedum* is still used in the mixes, the Mexican species can bring different structures, colours, heights and textures.

2.2.4.1 The use of Mexican Crassulaceae species on green roofs in Mexico

The amount of investigation on native species in Mexico is not substantial. Even though the local government of Mexico City is rapidly installing green roofs on its buildings, there are very few publications in regards to the survival of native species. One publication tested five Mexican *Sedums* in a 10 cm standard depth: *S. griseum, S. moranense, S. dendroideum* subsp. *praealtum,* the hybrids *S.* x *luteoviride*, and *S.* x *rubrotinctum,* as well as species of *Opuntia* and *Mamillaria* (Grau et al., 2005). The species were tested in 15 different substrate mixtures composed of three different volcanic materials: red-brown porous volcanic rock, white-grey pumice, and light grey pumice mixed with coir fibre, wood chips, worm compost and peat moss were tested but results have not yet been published (Grau et al., 2005).

In the Institute of Biology of the National Autonomous University of Mexico (UNAM) there are two display green roofs with *Sedum* x *rubrotinctum*, *Sedum pachyphyllum*, *Sedum dendroideum, Echeveria gigantea, Graptopetalum paraguayense*, *Graptosedum* “Vera-Higgings”, *Graptosedum* “Darley Sunshine”, *Sedum allantoides*, *Agave nayaritensis*, *Myrtillocactus geometrizans* and *Neobusbaumia polylpha* (Reyes-Santiago and Carbajal, 2009) but no research on survival has been performed. The botanical garden of the Centro de Información y Comunicación de Estudios Ambientales del Norte de América (CICEANA) in Mexico City, is a semi-extensive green roof composed of 56 % Cactaceae spp., 24 % Crassulaceae spp., 17% Agavaceae spp. and 3% Asteraceae spp. (CICEANA, 2009).There is no publication about the plant survival of the species they grow.

2.2.4.2 The selection & use of Mexican Crassulaceae species on green roofs across the world

Some Mexican Crassulaceae species have been used on green roofs in other parts of the world. Snodgrass (2006) published a guide to green roof plants in which he recommends the use of five Mexican plants and a hybrid with their hardiness classifications and their form of growth: *Sedum diffusum, S. griseum, S. mexicanum, S. moranense, S. stahlii* and *S.* x *rubrotinctum.* He is currently testing more Mexican species such as *Sedum booleanum* (Snodgrass, 2013). The species hardiness zones in the U.S. suggested by Snodgrass (2006) range from 8 to 10, according to the Hardiness map by the United States Department of Agriculture, equivalent to -12° C to +1.7° C (USDA, 1990). The proximity of Mexico and the US suggests the possibility of the survival of other Mexican species in some regions of United States, especially in the zones near the border of the two countries, which share a common climate.

In Michigan, Durhman (2007) measured the growth rate, coverage and survival of 25 succulent species in three depths (25 mm, 50 mm and 75 mm) to test their hardiness. The following species used in this experiment were Mexican: *Graptopetalum paraguayense* susp. *bernalense* Rose, *S. clavatum, S. confusum, S. mexicanum, S. moranense, S. pachyphyllum, S.* x *rubrotinctum* and the natural hybrid *S.* x *luteoviride, S.* 'Rockery Challenger' and *S.* 'Spiral Staircase'. According to Durhman *S. mexicanum, S. moranense* and *S.* x *rubrotinctum* had a good performance during the growing season, but by day 336 all the species were dead due to the extreme cold winter of Michigan, which that year had a minimum temperature of -24.3° C (Durhman et al., 2007).

As Dunnett (2008) points out when searching for suitable plants for green roofs there are two major factors to consider depending on the location of the roof, one is the drought tolerance, the other is the cold hardiness. In general, Mexican species do not experience minimum temperatures of the sort experienced in Michigan or prolonged exposure to sub-zero. Although in Durhman's research new *Sedum* spp. are explored for green roofs and the drought tolerance of these plants is considered, the temperature of their native habitat was not. If the hardiness of an exotic species is not known in a specific area, the minimum average temperature and the annual precipitation of its' native habitat can provide useful information about the needs of the species to survive.

In warmer climates, like Spain, research to increase the number of plants suitable for green roofs Mediterranean climates is performed. The key factors for the plant's survival in this area are the drought (especially during the summer with the hottest days and no rain) and the cold. The Mexican species, *Sedum palmeri* and *Sedum moranense* were tested on green roofs in Madrid, but as yet no results have been published (Gómez-Campo and Gómez 1996). *Sedums* from the Mexican Trans Volcanic Belt as described later in Section 2.3.5.4 might be suitable to withstand the cold of Madrid. For coastal Mediterranean areas with more moderate winters the following Mexican species have been suggested: *Sedum adolphii, Sedum allantoides, S. pachyphyllum, S. dendroideum* subsp. *praealtum, Sedum treleasei, Pachyphytum oviferum, Pachyphytum bracteosum, Graptopetalum paraguayense,* and *Graptopetalum macdougallii* (Gomez-Campo and Gomez-Tortosa, 1996), but the criteria for the selection was not explained.

In Australia the Growing Green Guide: A guide to green roofs, walls and facades in Melbourne and Victoria, Australia suggests the use of the Mexican species *Sedum pachyphyllum*, *S. mexicanum* and *S.* x *rubrotinctum* (State of Victoria, 2014). Nevertheless, due to the low evapotranspiration rates of these species, researchers like Farrell et al. (2013) encourage the use of other species with major cooling effects properties required for Southern Australia.

In the tropical climate of Singapore, *Sedum mexicanum* and *S. nussbaumerianum* have proved successful during two and a half years with only one supplemental watering after a three week drought period (Tan and Sia, 2005). The rainy season of this country is very erratic, with precipitation during the months of December to April, and the dry season from February to July. During the wet season constant rainfall for long periods is the norm, therefore succulent plants for Singapore need to tolerate drought and, during the rainy season, high moisture levels in their substrate (Tan and Sia, 2005). Tan suggests that these water availabilities extremes are the reason for the death of common species used in green roofs like *Sedum kamtschaticum, S. rupestre* and *S. spurium*. The success of these Mexican species in Singapore might be due to (for example) the annual average precipitation of the habitat of *S. nussbaumerianum* native to the town of Zacuatan in the State of Veracruz with a mean annual precipitation of 1600 mm. Species of the same region or other areas of Mexico with similar precipitation might work equally well in this Southeast Asian climate (Evans 1983, Vidal-Zepeda 1990).

2.3 Methodology for plant selection

2.3.1 Introduction to the plant selection methodology

It is easy and dangerous to generalize that all Crassulaceae species can grow on green roofs because of their succulence, CAM photosynthesis and other adaptations to withstand drought. The wide distribution of Mexican Crassulaceae species in different climates and environments show that in order to select successful species for green roofs, we need to select plants from environments similar to the roofs where we intend to grow them. For the selection of plants in accordance to the climate of their provenance, as described in Chapter 1, the Köppen-Geiger-Kottek updated climate classification map is used as a guide. Nevertheless, this system was conceived as a general map of the world's climates, therefore it standardizes large zones and loses climate details. One major example of this is climatic variances among different altitudes (García, 1973). The altitude in Mexico ranges from 0 to 5653 m.a.s.l. (Rzedowski, 1986), and within this variation of altitudes there is a variation of microclimates that is not present in the Köppen-Geiger updated climate classification map. In the same way, the whole UK territory is classified as (Cwb) warm temperate, winter dry, warm summer (Kottek et al., 2006). Nevertheless, there is variation in the mean minimum temperatures throughout the UK territory, that even though is not very wide, is wide enough to have repercussions for plant survival. Due to this lack of climatic detail it is necessary to use more detailed climatic information concerning the area of the buildings where the plants will be, and of the native microclimates of the habitats of the individual plant species.

The plant selection methodology proposed in this research to select species for specific climates comprises the following steps:

1. **Climatic characterization of the green roof site**

   Identification of the Köppen-Geiger-Kottek climate classification, of the destination area of the green roofs.

   To be able to identify candidate plant species for specific climatic zones a general and universal model the Köppen-Geiger climatic map is to be used as a frame work.

   Identification of additional climatic parameters of the green roof site such as minimum and maximum temperatures, and mean precipitation and precipitation distribution.

   This step is crucial to obtain a more in-depth knowledge of the microclimate of the destination where the plants are going to be planted. Of particular importance are the temperature extremes of the locality in combination with rain distribution.

2. **Analysis of target areas with potential candidate species**

   Identification of target areas sharing the same Köppen-Geiger-Kottek climatic classification.

The identification of zones with the same climatic classification can refine the possible search areas with possible suitable species. Although in some cases this match is not always possible (i.e. the territory does not share the analogous climatic types).

Analysis of areas according to their minimum and maximum extreme temperatures, mean precipitation and precipitation distribution.

This is first step before the identification of the microclimates located within the larger areas of the Köppen-Geiger-Kottek classification map. Or, when this match is not possible, it would be beneficial to find potential areas with similar microclimates to the destination area.

3. **Identification of areas with homologous microclimates to the destination area**
   This step targets the specific refine zones with the narrowed-down destination area. Sometimes it will match with mountain ranges since gradients in temperature are closely linked to altitudes and gradients. (In the case of Mexico it match with the Mexican physiographic zones).

4. **Identification of potential green roof candidate species from areas with homologous microclimates**
   This results in a first long-list of all possible plant species that may be suitable to be grow in the destination area. In this case, species from specific families, such as Crassulaceae, or species sharing specific physiological traits such as succulence can define the process.

5. **Characterization of chosen potential candidate plants species**
   Information of the identified plant species [such as: size, growth form, hardiness (if found in literature), aesthetics, native habitat and altitude] is obtained for as many plants as possible in the long-list.

6. **Thinning of potential species – producing the short-list**
   The available information pertaining to each plant species will be used to perform and initial sift of the most suitable plants species for the destination area. Species with a very slow growth or very poor aesthetic characteristics might not be desired. In some cases the propagation of a particular species is difficult and not enough plant material can be found. All these considerations will thereby create a realistic list of potential species to test on the selected green roof study site.

The next two sections of this chapter will focus on the more specific climatic conditions relevant to the two case studies and their equivalent in the Mexican territory in order to delimit zones with potential plant species. The first section will consider with more detail the environment of the roof representative of the climate (Cwb), **warm temperate, with dry winter, and warm summer** and the second, the environment representative for climate (Cfb) **warm temperate, fully humid, warm summer**. The sites where the plant species will be tested are southern of Mexico City, Mexico, for climate Cwb, and central Sheffield, UK for climate Cfb. The additional climatic parameters that will be considered are the minimum and average temperature of the cities, the annual average precipitation and the precipitation distribution. Due to the open exposure of both buildings, plants in their native habitats are fully exposed to the sun will be considered. Altitude data per se itself will not be included for the plant selection, since the temperature factor is more important, especially at extreme temperatures.

After the climatic considerations, a brief characterization of the physiographic zones of Mexico will be presented since, as shown in the next sections, the physiographic zones are closely related to the climatic conditions of the Mexican territory. Following the physiographic zones section, a description of the types of vegetation from the selected physiographic zones where Crassulaceae species grow in Mexico is presented. The aim of these sections is to understand the vegetation types where the species grow and use them as a final parameter for the selection of the plant species. In Figure 2.3.1 a diagram presents the stages and flow of information for the plant selection undertaken in this study in accordance to the plant selection methodology:

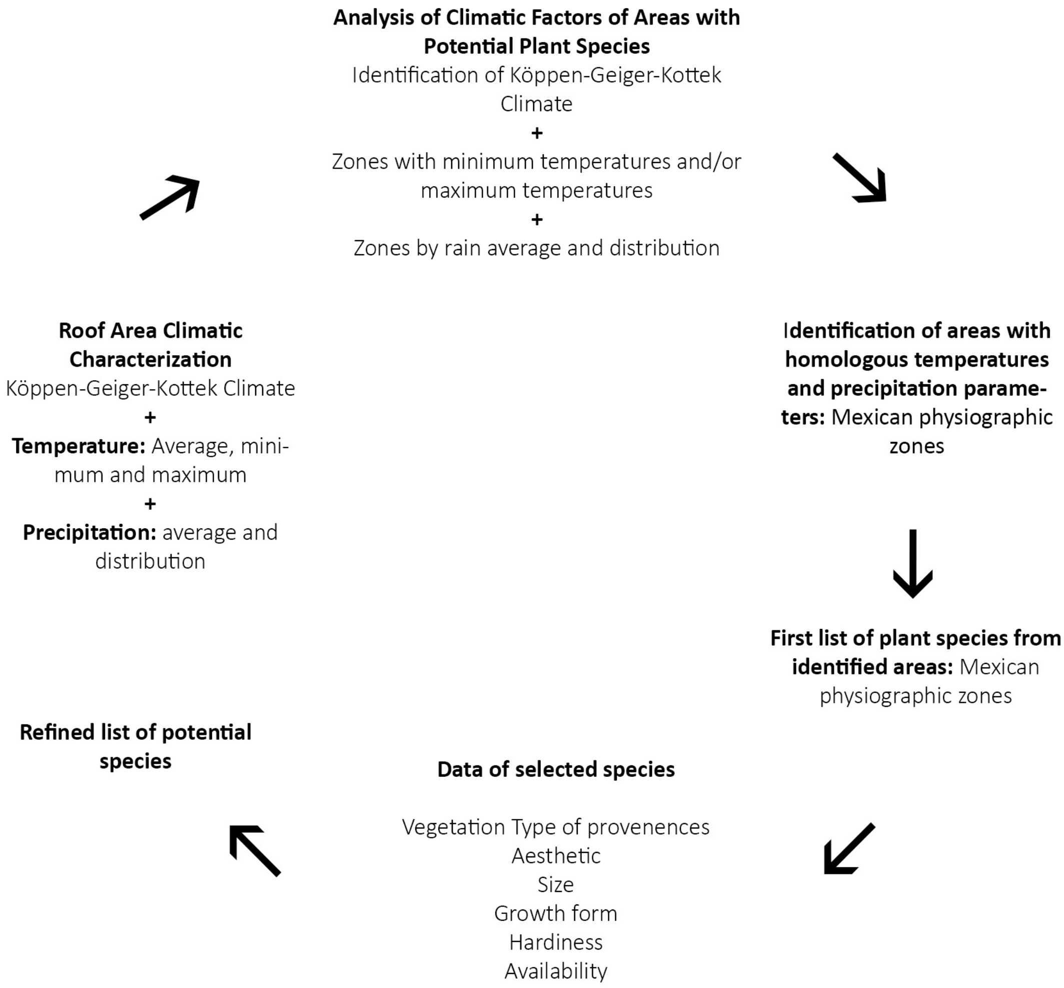


Figure 2.3.1 Steps of methodology of plant selection.

2.3.2 Roof Environment in Cwb: Mexico City

2.3.2.1 Temperature: annual average temperature, maximum and minimum

In Mexico City the average annual temperature is 15.3°C (SMN-Mexico, 2010a). The minimum annual temperature is 9.5°C (SMN-Mexico, 2010b), with the coldest temperatures occurring during January. In the outskirts of the city the temperature can drop to around 0°C (Jáuregui, 2000). Frost events occur 2 to 15 times a year in the centre of the city and 30 to 50 times a year in the outskirts. The minimum extreme temperatures during a period of 30 years range from -1 to -4 °C in the centre of the city down to -12 °C in the outer skirts (Jáuregui, 2000). The average maximum is 23.4°C (SMN-México, 2010), with the hottest month being May with 26.5°C. the maximum extreme temperatures during a period of 30 years ranges from 36 to 38 °C (Jáuregui, 2000) .

2.3.2.2 Annual precipitation and distribution

In Mexico City annual precipitation ranges from 400 mm to 500 mm in the northeast to 700 to 1200 mm in the south of the city (Jáuregui, 2000). Precipitation in Mexico City is highest during the summer, regularly starting in late May with June, July, August and September finishing in October with the wettest months being July and August with 160 to 225 mm, depending on the zone and the driest months are December to February with only 5 to 10 mm of rain (Jáuregui, 2000).

2.3.3 Targeting Mexican homologous environments to Cwb

The methodology for the plant selection for this research will consider homologous environments or habitat templates to target areas with potential species. This first section will start with the exploration for Cwb climates (warm temperate with dry winter and warm summer) and the specific case study of Mexico City (Kottek et al., 2006). This section will present maps of the minimum temperatures, annual precipitation and distribution in Mexican territory and the zones with matching characteristics for each parameter will be selected. **Combining two or more climatic criteria should improve greatly the livelihood of successful candidate selection.** Zones with two or more parameters will be considered as areas with possible plant species for each climate.

2.3.3.1 Minimum temperatures of Mexico

Selected zones for climate Cwb according to the minimum temperature

Considering that the minimum temperatures can drop to 0°C, zones in the range between <0°C to 18°C will be considered for plant selection for Mexico City: Colours grey, purple, lime turquoise and lime green of the Figure 2.3.2. It is important to mention that mean minimum temperatures in the Mexican territory decrease with greater altitude, like in any part of the world and greater latitude, since the country is located in the Northern hemisphere. This means that the grey zones in Figure 2.3.2 that correspond to the lowest mean minimum temperatures in the South of the territory will mainly correspond to higher altitudes. In contrast some of the grey areas of the North of the country may correspond to zones with lower altitudes, but their lower minimum temperatures are due to their higher latitude.

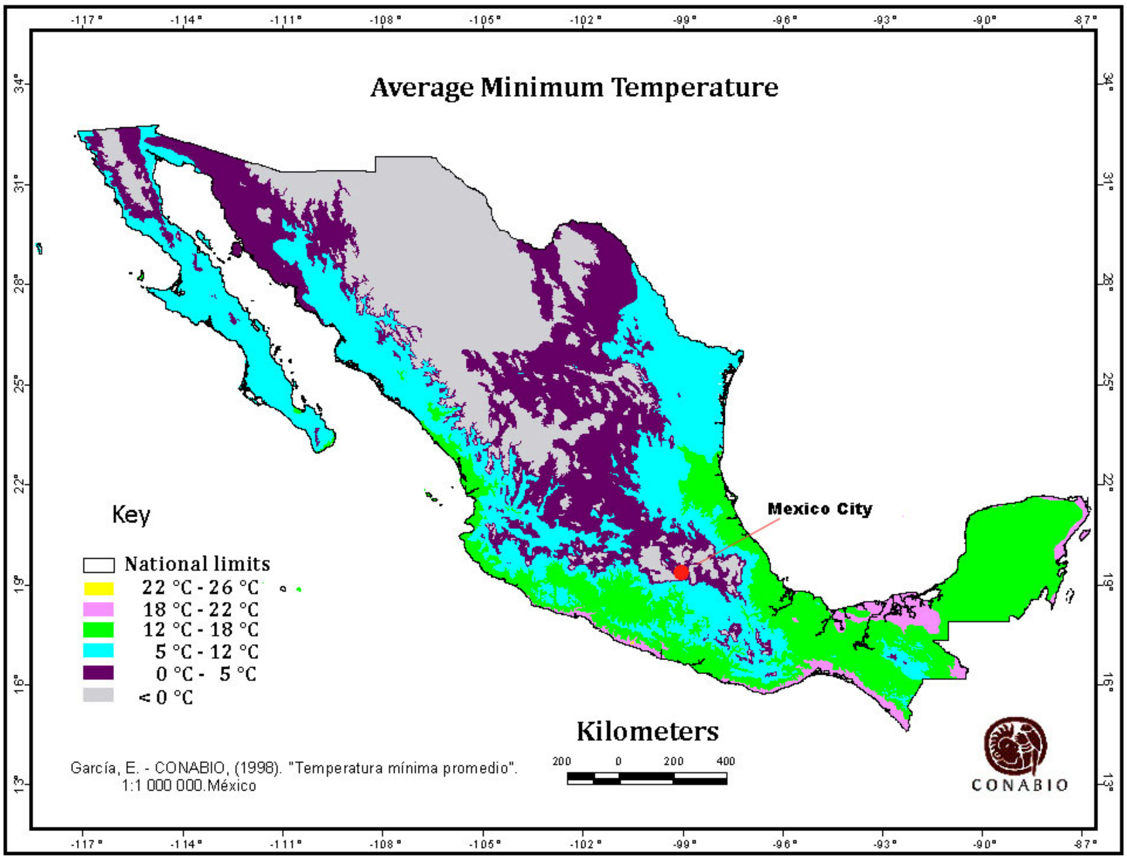


Figure 2.3.2 Average Minimum Temperatures across Mexico (García, 1998).

The average maximum temperature in Mexico City is 23.4°C (SMN-México, 2010), with the hottest month being May with 26.5°C (Jáuregui, 2000). The majority of Mexico has an average annual maximum temperature that ranges from 17 to 34 °C, and some cooler zones also have extreme high temperatures during the hottest months. Therefore, the species selected through the rest of the criteria presented here, will be checked independently for maximum temperatures in the microclimate they experience in their habitat. Nevertheless, after the first selection, species growing only in shaded areas will be removed from the list since they might not tolerate the high sun exposure of the roof setting.

2.3.3.2 *Mean annual precipitation*

Selected zones Cwb according to average precipitation

Due to the shallow substrates on the roof, zones with a precipitation from 125 mm to 1200 mm will be selected. Areas coloured light orange, deep orange, light green and lime green from Figure 2.3.3, corresponding to the required precipitation will be selected.

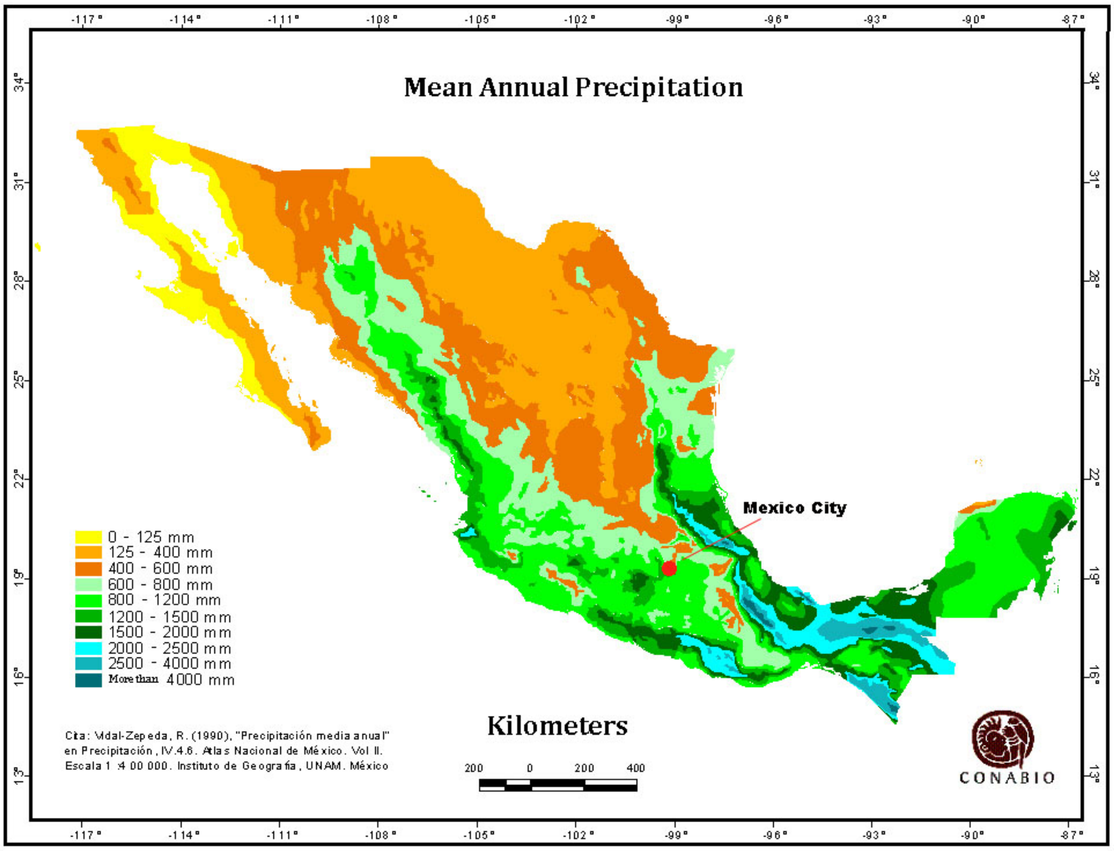
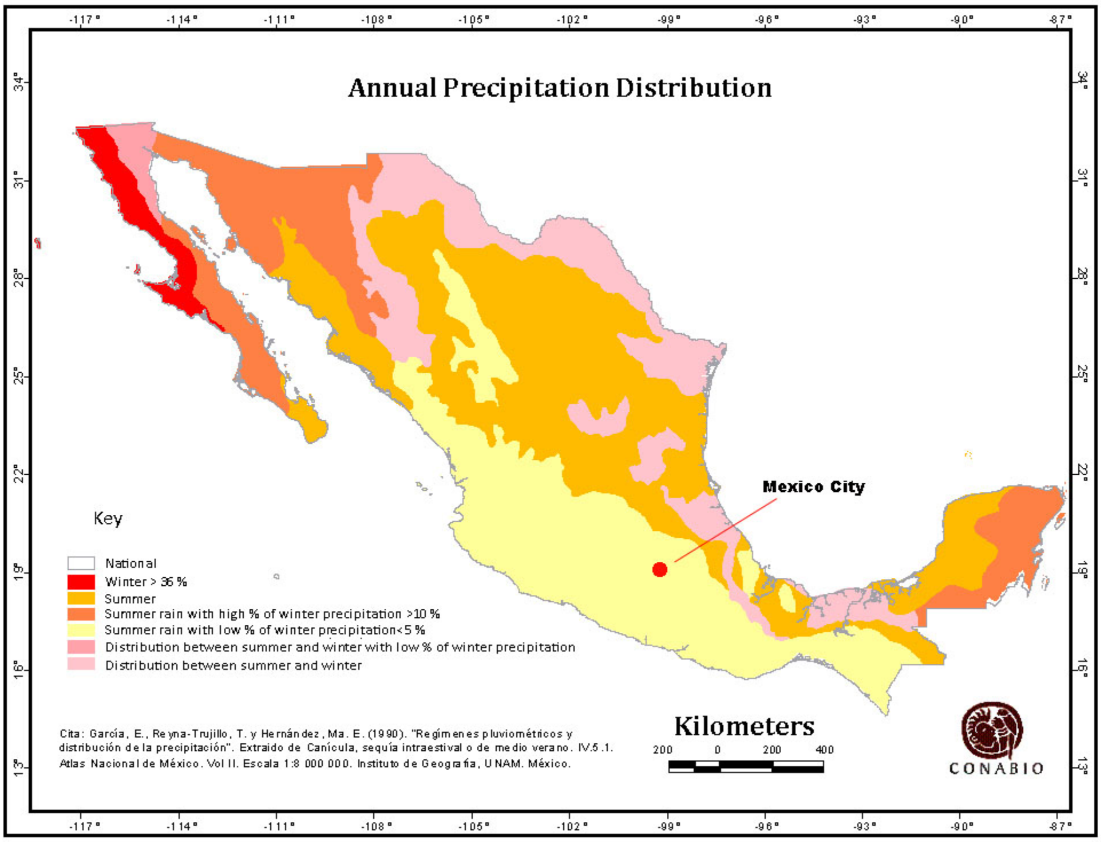


Figure 2.3.3 **Mean Annual Precipitation (Vidal-Zepeda, 1990).**

2.3.3.3 *Annual precipitation distribution*

Selected zones Cwb according to precipitation distribution

In Mexico City the rainy season occurs during summer as in the majority of the country, therefore only the zones with a high winter precipitation will be excluded, corresponding to the area in red in Figure 2.3.4.



Cita: García, E., Reyna-Trujillo, T. y Hernández, Ma. E. (1990). "Regímenes pluviométricos y distribución de la precipitación". Extraido de Canícula, sequía intraestival o de medio verano. IV.5.1. Atlas Nacional de México. Vol II. Escala 1:8 000 000. Instituto de Geografía, UNAM. México.

Figure 2.3.4 Annual Precipitation Distribution (García et al., 1990)

2.3.3.4 *Over lapping zones and the physiographic provinces of Mexico for Cwb*

The Mexican territory has a wide range of geographical features that have been classified in different physiographic provinces. After applying the climatic criteria for green roofs in climates Cwb, the following physiographic provinces appeared as zones with a high probability of holding potential species: The Sierra Madre Occidental, the Sierra Madre Oriental, the Mexican Transverse Volcanic Belt, the Northern Mountain System of Oaxaca and the Mexican Plateau (Figure 2.3.5). Even though some of the territory has been selected, there is still a high diversity of habitats within each province. For this reason, after presenting the selection methodology for climate Cfb, a more detailed reading of the potential provinces will be done through their vegetation types thereby refining the selection criteria and methodology.

2.3.4 Roof Environment in warm temperate fully humid warm summer Cfb: Sheffield UK

In this section the initial steps for the plant selection for climate Cfb will follow the same procedure as with the case study for Mexico City. According to the revised Köppen-Geiger climate classification by Kottek (Kottek et al., 2006) England is classified under warm temperate fully humid with warm summer. Taking in consideration that this is a broad classification, we need to have more local data about the climate of Sheffield.

2.3.4.1 Temperature: annual average temperature, maximum and minimum

The average temperature of Sheffield is 9.5°C, the average minimum temperature is 6.3°C, and February is the coldest month with an average of 1.7°C. The average maximum temperature is 13.4°C, with July as the hottest month with an average of 21.1°C (Met-Office, 2013). Frost occurs for a yearly total average of 33.8 days during October to April. February has the highest number of frosts with nine days a month (Met-Office, 2010a).

2.3.4.2 Annual precipitation and distribution

The annual precipitation for the city of Sheffield is 824.7 mm (Met-Office, 2010b) with the highest distribution during winter and the lowest during summer. The wettest month of the year is December with an average of 86.7 mm while the driest is May with 53.8 mm (Met-Office, 2010b). During the coldest days of winter the precipitation is present in the form of snow.

2.3.4.3 Targeting Mexican homologous environment to Cfb

Selected zones of minimum temperature for climate Cfb, Sheffield, UK

In the map of the minimum average temperatures of Mexico (Figure 2.3.2), the zones that show the lowest temperatures (< 0°C to 12°C) are particularly relevant to the study. Even though the minimum average temperature in Sheffield is 6°C, zones with lower average temperatures will be considered due to the extreme minimal temperatures and the lower temperatures some roofs experience due to their structure. This corresponds to grey, purple and turquoise zones of Figure 2.3.2.

Selected zones of average precipitation for climate Cfb, Sheffield, UK

As the precipitation in Sheffield is 824.7 mm (Met-Office, 2010a), all areas with a minimum of 600 mm (pale green in Figure 2.3.3) and a maximum of 1200 mm (bright green) will be considered for UK plant selection.

Selected zones of rain distribution for climate Cfb, Sheffield, UK

As the annual rain distributions in the UK is higher during the autumn/winter period and lower during spring/summer, zones with higher amount of precipitation during winter will be selected (i.e. the red, light pink, and orange areas on the map in Figure 2.3.4).

Overlapping zones and the physiographic provinces of Mexico for Cfb

Through the overlapping of the climatic areas on the Mexican territory the following physiographic zones were selected for UK plant selection: Sierra Madre Occidental, the Sierra Madre Oriental, the Mexican Transverse Volcanic Belt, the Northern Mountain System of Oaxaca, the Mexican Plateau and the Mountain System of Baja California (Figure 2.3.5).

2.3.5 The selected physiographic provinces of Mexico pertinent to the study

After applying the above criteria to the Mexican territory, the areas that combined two or more of the above climatic characteristics coincided with zones that are either delimited by or are themselves ranges of mountains. This phenomenon is not unusual since one of the selection criteria is the minimum average temperatures that are usually linked to high altitudes (Challenger, 2003) in the Mexican territory as elsewhere. The mountains and plains have been grouped by others as the Mexican physiographical provinces (González-Medrano, 2004, Rzedowski, 1986). There are fifteen or twelve recognized physiographic provinces in Mexico depending on the author. This research will work with the classification presented by Rzedowski (1986), who has compiled the most detailed study of the Mexican habitats (Fig. 2.3.5) based on the shared temperature + precipitation data. From the fifteen physiographic provinces, six have been selected for this research.

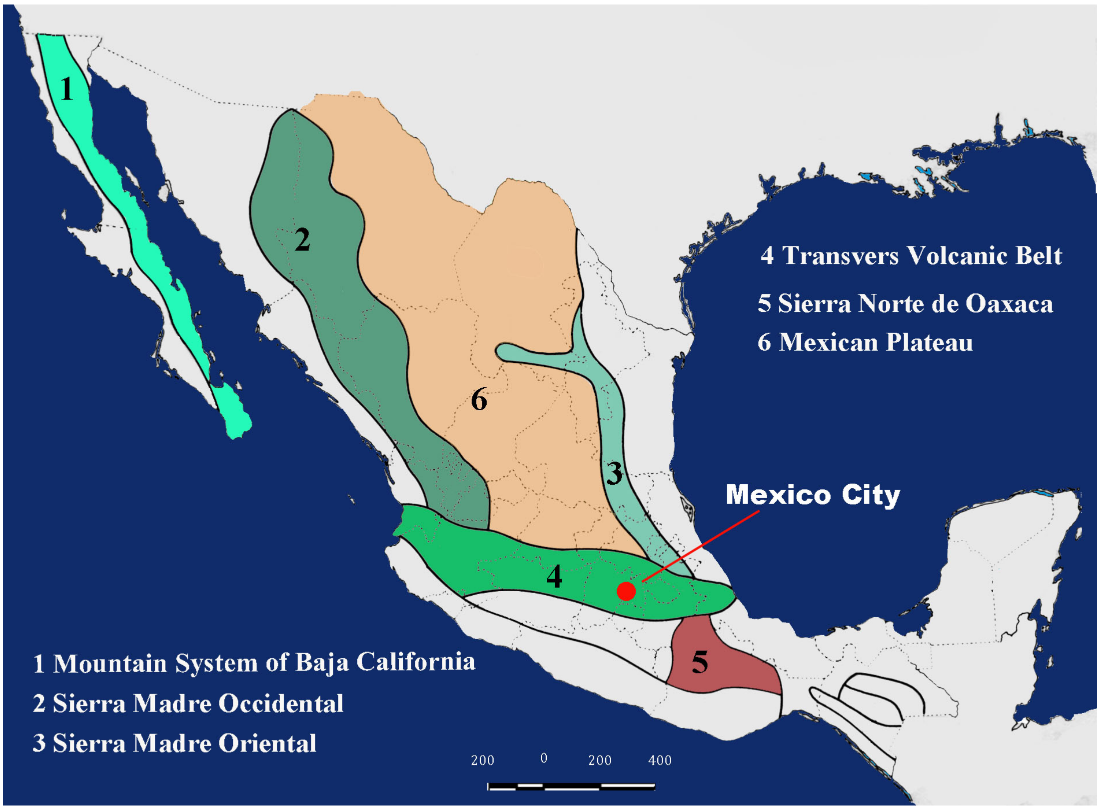


Figure 2.3.5 Selected physiographic provinces of Mexico: map adapted from (Rzedowski, 1986)

The Sierra Madre Occidental, the Sierra Madre Oriental, the Mexican Transverse Volcanic Belt, the Northern Mountain System of Oaxaca and the Mexican Plateau are targeted areas for **both**

Mexico City and Sheffield, while the Mountain System of Baja California with a higher portion of winter rains will **work only for Sheffield** (Figure 2.3.5).This section will present a brief analysis of the six targeted zones. This will be followed by a description of the different types of vegetation that grow in the six zones and a table to summarize each physiographic province and the types of vegetation it presents

2.3.5.1 Mountain System of Baja California

The Mountain System of Baja California (Figure 2.3.5-1) runs along the whole Peninsula of California from North to South. On the northern side are the higher ranges of Sierra de Juárez and San Pedro Mártir with altitudes greater than 3000 m (González-Medrano, 2004, Rzedowski, 1986). This is the zone of interest for this research since its precipitation is higher than on the rest of the Peninsula and has a greater distribution during winter. The precipitation characteristics and the low temperatures at higher elevations make it a candidate zone as an homologous habitat to the roofs of Sheffield. These ranges run parallel to the coast of the Gulf of California and are the southern continuation of the Mountains of San Jacinto and the Mountains of Santa Ana in the U.S. The slopes of both ranges are gentler on the western side, while very steep on their eastern sides. Both ranges are formed by granite, crystalized schist and metamorphosed limestone (Ordoñez, 1941).

2.3.5.2 Sierra Madre Occidental

This mountain system (Figure 2.3.5-2) starts from the border with Arizona, U.S., and continues south covering part of the states of Sonora, Chihuahua, Durango, Sinaloa, Nayarit, and Zacatecas, until it is intercepted by the Transverse Volcanic Belt on the states of Nayarit at river Santiago (González-Medrano, 2004, Rzedowski, 1986). It runs parallel to the Pacific Coast and it separates the North Occidental Coastal Plain from the Mexican Plateau. It is the longest and most continuous mountain system in Mexico at around 1400 km in length (Ordoñez, 1941, Rzedowski, 1986). The average altitude of the higher zones ranges between 2000 to 2500 m with just above 3000 m for the highest points (Rzedowski, 1986). Most of the system is constituted of igneous rocks of volcanic origin. The geologic characteristics and the rivers flowing to the pacific contribute to the formation of many deep canyons such as the Cañón del Cobre (González-Medrano, 2004, Rzedowski, 1986).

2.3.5.3 Sierra Madre Oriental

The Sierra Madre Oriental (Figure 2.3.5-3) is the mountain system that begins at the edges of the Rio Bravo in the border with the United States in the northeast of the country and extends towards the southeast to the centre of Puebla state. This mountain system is a continuation of the Big Bend in western of Texas, U.S. (Ordoñez, 1941). It takes in part of the states of Chihuahua, Coahuila, Nuevo León, San Luis Potosí, Querétaro, Tamaulipas, Hidalgo, Puebla and Veracruz (González-Medrano, 2004, Rzedowski, 1986). The mountains of this system are formed by sedimentary marine rocks, limestone and mudstones mainly of the Mesozoic era and, through erosion, deep ravines and high cliffs have been formed (Ordoñez, 1941). Precipitation on the Sierra Madre Oriental is distributed mainly from May to September. With higher rains on the eastern side due to the humid winds from the Gulf of México (Ordoñez, 1941), this area may well possess more appropriate plant species for the UK.

2.3.5.4 Neo-Volcanic Transverse Belt

The Neo-volcanic transverse belt (Figure 2.3.5-4) is a mountain system situated between the parallels 19° and 20°. It occupies part of Nayarit, Jalisco, Colima, Michoacán, State of México, Morelos, Puebla, Tlaxcala, Veracruz and Mexico City. It is formed mainly by high quantities of different igneous elements such as volcanic rocks and lava spells (González-Medrano, 2004). Some of the volcanoes that form part of this range are Pico de Orizaba (5,6010 m), Popocatépetl (5,465 m) Itztaccíhuatl (5,230), Citlaltepetl (4,680), Malinche (4,340 m) and Cofre de Perote (4,090 m) (González-Medrano, 2004, Rzedowski, 1986). A characteristic of this system is the formation of vast enclosed basins such as the Valle de Mexico, where Mexico City is located (González-Medrano, 2004). The average annual precipitation of these mountains ranges between 800 mm to 1600 mm although some areas present a lower average. Only up to 5% of the rains occur during winter. The extreme minimum temperature goes down to -5° while some of the highest eastern zones drop down to -10° (Rzedowski, 1986). Plants in the zone may be very hardy, but perhaps not under the cold wet conditions of the UK.

2.3.5.5 Northern Mountain System of Oaxaca

Although the Northern Mountain System of Oaxaca (Figure 2.3.5-5) is a term no longer used, and instead many authors have joined this area to the Sierra Madre del Sur (INEGI, 2011b, Ramamoorthy et al., 1998), for the purposes of this work we will be interested only in the area designated as the Northern Mountain System of Oaxaca. This mountain system is located in the north of Oaxaca, and is a prolongation of the Sierra Madre Oriental that has been interrupted by the Transverse Volcanic Belt. The Northern Mountain System of Oaxaca is formed by the smaller ranges, Sierra Norte de Oaxaca, the Sierra Mixteca, and Chinatla Alta (Figueroa-Navarro et al., 2005, Rzedowski, 1986). Due probably to the fact that it is the product of both the Sierra Madre Oriental and the Transverse Volcanic Belt, it is highly mountainous with few plains and many elevations higher than 1000 m, with the Zempoaltépetl as the highest mountain at 3400 m (Rzedowski, 1986).

2.3.5.6 The Mexican Plateau

The Mexican Plateau (Figure 2.3.5-6) is an area stretching from the state of Chihuahua and Coahuila to Jalisco, Michoacán, the State of Mexico, Tlaxcala and Puebla (Rzedowski, 1986). It is located between the Sierra Madre Occidental, the Sierra Madre Oriental and the Mexican Transverse Volcanic Belt (González-Medrano, 2004). It is the southern continuation of the Basin and Range Province of Arizona and New Mexico in the U.S. (Ordoñez, 1941). The altitude of this zone ranges from 1000 to 2000 m. It is composed mainly of plains and isolated ranges of mountains. In the northern part, most of the mountains are formed by sedimentary rocks while the southern areas are formed by volcanic and eruptive rocks, basalt, rhyolite, andesite (Ordoñez, 1941). In the southern parts, land on depressions are formed from alluvial and lacustrine sediments (Ordoñez, 1941).

As described in the model of the plant selection methodology (Figure 2.3.1), after the identification of areas with homologous climatic conditions, an initial list with potential species from the selected physiographic zones was generated for climates Cwb and Cfb (Annex 1). Since the climatic data of the physiographic zones is still very extensive, the first criteria to thin the plant list for each climate (Cwb and Cfb) **is the type of vegetation of the provenance of the plants**. The type of vegetation provides more detail of the climatic conditions of the provenance of the plants. The next criteria include information about plant growth form, aesthetics and hardiness if found in the available literature. For the plant list of Cwb (Mexico City), plants that only grow in shaded places will be extracted from the list as well deemed unsuitable for high light intensity roof tops. The next section presents the analysis of the type of vegetation which candidate plants for the roofs of Cwb and Cfb climates may be found.

2.3.6 The types of vegetation of the selected physiographic provinces

The selected physiographic provinces for our plant selection hold a wide diversity of vegetation types. Some of the many causes of this diversity include the merging of the Nearctic and the Neotropic ecozones, the diverse climatic factors due to the humid air current from the Gulf of Mexico and the Pacific Ocean, diverse altitudes of the terrain, its' latitudinal and longitudinal extension and its' river systems. Also, due to the rugged topography, natural barriers to genetic migration have resulted in geographical isolation and allopatric speciation, contributing to the high degree of endemism within the Mexican biomes (Challenger and Soberón, 2008, González-Medrano, 2004). This is particularly relevant for members of the Crassulaceae.

There have been many attempts to classify the types of vegetation of Mexico. While authors such as Miranda and Hernandez (Miranda and Hernández, 1963) , described 32 communities, Rzedowski presented a system with 10 main types of vegetation. This simplification was to avoid misconceptions due to lack of information and arbitrary differences between concepts such as forests and jungles (1986). According to Challenger and Soberón (2008) , the system most used today is the one proposed by the INEGI (National Institute of Statistics and

Geography), due to its digital platform, which presents 50 types of vegetation. Recent modifications help it to work in conjunction with Rzedowski's (Challenger and Soberón, 2008).

The following sections will introduce a table (Table 2.3.1) with the type of vegetation present on each the selected physiographic zones that support Crassulaceae species and that can possibly create microclimates with similar range to our case studies. This will be followed by brief descriptions of the types of vegetation. The description will follow the general Rzedowski (1986) classification with some particularities from the INEGI classification as presented by Challenger and Soberón (2008) and extra information from other authors in regards to particular flora. The use of these later classification systems are on improvement of Rzedowski (1986) due to the introduction of interactive GIS mapping and other electronic resources, however Rzedowski is still as the authority overall. As described in the methodology model, the provenance of the first list of potential species was compared with the suitable vegetation types for the roofs of the Cwb and Cfb climates for an initial sift and refinement of the list.

Vegetation Types Classifications and Physiographic Zones

Generic Vegetation Type	Detailed Vegetation Type	Physiographic Zones
Temperate forests of conifers and broadleaf trees	*Quercus* Forest	TVB, SMO, SMOC, NMSO, MP, MSBC
	Pinus Forest	TVB, SMO, SMOC, NMSO, MSBC
	Mixed *Quercus*-Pine Forest	TVB, SMO, SMOC, NMSO, MP
	Other Conifers	TVB, SMO, SMOC, NMSO, MSBC
Xerophilous scrub	Succulent xerophilous scrub	MP
	Woody xerophilous scrub	NMSO, MP, MSBC
	Woody xerophilous scrub: Chaparral	SMO, MSBC
	Woody xerophilous scrub: Piedmont	SMO, MP
	Herbaceous xerophilous scrub: Pedregal	TVB,
Grassland	Alpine and subalpine vegetation	TVB
	Semiarid grassland	SMOC, MP
	Semiarid grassland: Mezquital	MP
Tropical deciduous forest	Tropical deciduous forest	TVB, SMOC, SMO, NMSO, MSBC

Table 2.3.1 Table based on maps of Physiographic zones and Main types of Vegetation of Mexico. Key: TVB Neo-Volcanic Transverse Belt, SMO Sierra Madre Oriental, SMOC Sierra Madre Occidental, NMO Northern Mountain System of Oaxaca, MP Mexican Plateau, MSBC Mountain System Bajacalifornia. Based on (INEGI, 2011b, INEGI, 2011a).

2.3.6.1 Temperate forests of conifers and broadleaves trees

Temperate forests of conifers and broadleaves is the term Challenger (2008) uses to group nine types of temperate forests according to the classification of INEGI of 2005: Dominated by *Picea*, *Cupressus*, *Quercus*, *Quercus*-Pinus, *Abies*, *Pinus*, *Pinus*-*Quercus*, *Juniper* and Conifer shrubs (2008) or Rzedowski's Forests of *Quercus* and Forests of conifers (1986). This section presents a description of the Forests of *Quercus* and the Forests of *Pinus,* since these are the more abundant genera in these vegetation types and of major importance to this research, and a brief description of other conifer forests.

Quercus forests

In Mexico the *Quercus* forests from temperate climates are very abundant, have great variation in composition and structure, and are closely associated with *Pinus* forests. Both of these forests, separated and mixed, produce the biggest vegetative cover in Mexico after the xerophilous scrubs (Challenger, 2003). *Quercus* forests are usually distributed in the middle altitudes of mountains, but can grow from sea level up to 3000 m (Challenger and Soberón, 2008, Rzedowski, 1986).

Quercus forests can be found in all the states of Mexico, with the exception of the Peninsula of Yucatán. They are present in the Sierra Madre Occidental and Transverse Volcanic Belt, but are dominant in the Sierra Madre Oriental (Rzedowski, 1986). In the colder zones of the Mexican Plateau, dry oak forests are established on steep slopes with species such as *Quercus deserticola*, *Opuntia spp.* and *Pinus teocote* (Hágsater et al., 2005). Examples of Crassulaceae communities found in dry forests of *Quercus laeta* in Tepoztlán, on the Transverse Volcanic Belt, grow on intrusive igneous soils with species such as *Cremnophila nutans* endemic to the area in association with species of the genera *Agave, Tillandsia* and lithophytic orchids of the genera *Epidendrum, Nemacoinia* and *Stanhopea* (Hágsater et al., 2005). Although there are a high number of different *Quercus* forests, those presented here are the most relevant to this research.

Pinus forests

The pine forests have the greatest distribution of all the conifer forests and can be found in all the mountain ranges of the country, with the exception of the state of Yucatán (Challenger and Soberón, 2008, Rzedowski, 1986). Their distribution runs from subalpine areas with species like *Pinus hartwegii* and *Pinus culminicola* to pinyon *Pinus pinceana* and *Pinus cembroideum* in semiarid climates (Hágsater et al., 2005, Rzedowski, 1986). The *Pinus* forests have been recorded in zones as low as 150 m above sea level, but usually they grow in areas with an altitude between 1500 to 3000 m and are the only trees that can grow in the low temperatures of high altitudes up to 4100 m (Rzedowski, 1986).

Pinus forests are found on igneous acid soils like those in the northern part of the Sierra Madre Oriental, where the sedimentary soil and limestone are substituted with volcanic soils. They can develop either on deep or very shallow soil, providing they have good drainage (Rzedowski, 1986). They are found in the extreme north of the Baja California Peninsula, in the Northern Mountain System of Oaxaca, in the Sierra Madre Occidental and the Transverse Volcanic Belt (Rzedowski, 1986). Most pine forests can withstand droughts, frosts and fires and can grow in low nutrient soils (Merilo et al., 2013, Rzedowski, 1986); some of these characteristics are similar to the green roof environment and, therefore open areas of pine forests, exposed to solar radiation, can be a source of plant material for green roofs, especially the areas of shallow soils.

The *Pinus* forests display a wide range of communities from pure pine forests with only one tree stratum to two or three strata with species of *Quercus*, *Abies*, *Buddleja*, *Cupressus* etc.. Examples of communities of Crassulaceae species in *Pinus* forests are those of *Echeveria craigiana* (Walther, 1952). This plant grows in the under layer of pines with shrubs from the genera *Senecio*, *Salvia*, *Fuchsia*, *Salix*, *Agave*, *Desmodium*, *Satureja*, etc. Some of the associated herbaceous families are Rosaceae, Umbilliferae, Lilaceae, Iridiceae, Cruciferae, etc.

(Rzedowski, 1986). *Echeveria shaviana* can also be found in pine and oak forests (Figure 2.3.6 A and B) growing on big rocks under the shadow of the trees (García-Morales, 2013).

Figure 2.3.6 A) *Echeveria shaviana* and B) Pine forest West of Ciudad Victoria, Tamaulipas, habitat *E. shaviana*. Photo (García-Morales, 2013)

Other conifers

There are other conifer forests dominated by genera such as *Juniperus,* with the highest distribution after pines, or *Cupressus* which in very few places is the dominant genus (Challenger, 2003, Rzedowski, 1986). *Juniperus* forests are usually a transition between temperate sub humid regions and arid and tropical sub-humid zones (Challenger and Soberón, 2008). *Abies* forests are of very restricted distribution in Mexico found usually in the areas with high humidity and low temperatures (Challenger and Soberón, 2008), which could be of use in the identification of UK candidate species. Forests of *Picea* and *Pseudostuga* grow in similar environments to the *Abies* forests and sometimes even grow together, although *Pseudostuga* usually grows in drier zones (Rzedowski, 1986). In woodlands of *Abies* sometimes the understory is underdeveloped due to the lack of light, on the *Abies* forests from the Iztaccihuatl volcano, *S.* x *amecamecanum* can be found in relation with some ferns and communities with species associated with subalpine vegetation, as well as *S. minimum* (Clausen, 1959). Because of the low-light environment of these forest floors may shade tolerant Crassulaceae could be unsuitable for green roof culture, unless the roof is shaded.

2.3.6.2 Xerophilous scrub

Xerophilous scrub is the name under which Rzedowski (1986) and Challenger group 15 types of vegetation that can be found on the INEGI's 2005 (2008) classification. These types are: *Crassicaule* scrub, *sarcocaulous* scrub, thorny scrub of Tamaulipas, *rosettophyllous* desert scrub, *microphyllous* desert scrub, subtropical scrub, chaparral, sub-mountain scrub, *rosettophyllous* coastal scrub, *sarco-crassicaule* cloud scrub, *halophyte* vegetation, *mezquital*, *gypsophyte* vegetation, vegetation of sandy deserts (Challenger and Soberón, 2008). In this section will follow the grouping system presented by Challenger where the 15 types of vegetation are categorized according to their composition and their dominant species as woody, succulent and herbaceous scrubs (Challenger and Soberón, 2008), but only the types relevant to this research will be presented, where potential Crassulaceae species for Cfb and Cwb can be found.

The soils of most of the xerophilous scrubs range from pale grey to red colour, and with a variety of textures, from rocky to sandy. Generally they have low organic content but are high in nutrients, with pH ranging from 6 to 8.5. Some of the soils can be deep while others are very shallow on top of lava rocks (Rzedowski, 1986). This type of vegetation is found in 40% of the Mexican territory, especially in the Mexican Plateau and in the peninsula of Baja California and is usually short and of low density (Rzedowski, 1986).

Woody xerophilous scrub

The woody xerophilous scrub can be formed by microphyllous scrubs with species like *Larrea tridentata*, one of the bushes with highest distribution on the country, sometimes in association with *Flourensia cernua* and other genera includes *Acacia, Agave, Brusera, Condalia, Opuntia* and *Yucca.* (Challenger and Soberón, 2008, Hágsater et al., 2005, Rzedowski, 1986). The Chaparral is another form of woody xerophilous scrub, usually dominated shrubby *Quercus hypoxantha, Q.intricata, Q. invaginata* and *Pinus cembroides* and other species such as *Dasylirion palmeri, Mimosa biuncifera and Rhus aromatica.* (Challenger and Soberón, 2008, Hágsater et al., 2005, Rzedowski, 1986). The piedmont scrub, another woody scrub is usually located in the Sierra Madre Oriental. This scrub is about 3 to 5 m in height and most of the shrubs are evergreen. Species are *Cordia boissieri, Acacia rigidula* and *Zanthoxylum fagara*. (Canizales-Velázquez et al., 2009, Rzedowski, 1986). Species of *Crassulaceae* growing in this type of vegetation are *Echeveria bifida* in association with *Larrea tridentata* (Nájera Quezada et al., 2014).

Succulent xerophilous scrub

This kind of scrub is usually formed by families of succulent plants such as Agavaceae, Cactaceae, Crassulaceae and Fouquieriaceae all of them with a high number of endemic species (Challenger and Soberón, 2008). Some communities that belong to this kind of scrub are dominated by rosette from genera such as *Agave*, *Dasylirion*, *Hechtia* and *Nolina* (Hágsater et al., 2005, Rzedowski, 1986) (Figure 2.3.7 A and B). Other communities are dominated by *Opuntia* spp. or by columnar cacti such as *Cephalocereous* or *Neobuxbaumia.* In rosette dominated scrubs Crassulaceae species such as *Echeveria unguiculata* and *Echeveria walpoleana* grow on arid rock stone crops in association with *Selaginella lepidohylla*, *Hechtias* and *Dasylirion* (García-Morales, 2013).

Figure 2.3.7 A) *Echeveria unguiculata* and its habitat B) Rosettophyllous scrub in Miquihuana, Tamaulipas, photo permission of the author (García-Morales, 2013)

Herbaceous xerophilous scrub

This scrub is usually halophytic and has gypsophile vegetation (Challenger and Soberón, 2008) such as *Amaranthus scleropoides* on saline soils, *Tidestromia gemmate* on gyspsiferous soils and *Tidestromia lanuginosa* on both (Sánchez-Del Pino et al., 1999). A very peculiar scrub described by Rzedowski as herbaceous xerophilous scrub (Rzedowski et al., 2010) is the one growing on a large lava current from the volcano Xitle in Mexico City. This *malpaís* or *pedregal* (bad country or rockery) as it is often called, is of particular interest for this research since the roof for the Mexican experiments trials is located in this area. In the pedregal a very diverse flora can be found due to the different microclimates experienced in the lava formations.

Figure 2.3.8 *Echeveria gibbiflora* in Reserve of the Pedregal of San Angel, Mexico City.

Plant communities with Crassulaceae species such as *Echeveria gibbiflora* (Figure 2.3.8) and *Sedum oxypetalum* grow in association with *Senecio praecox*, *Muhlenbergia robusta,* other suculents like*, Talinum napiforme, Manfreda scabra,* annuals such as *Tagetes lunulata* and

Zinnia peruviana, some shrubs like *Begonia gracilis, Salvia Mexicana* and trees such as *Buddleja cordata*, *Brusera fagaroides* and *Brusera cuenata.* Some bubl species found in the Pedregal habitat are *Zephyrantes sessilis, Milla biflora* and *Trigidia pavonia.* Vegetation of these types are commonly found on the Volcanic Transverse Belt (Castillo-Argüero et al., 2004, Clausen, 1959).

2.3.6.3 Grassland

Grassland or *zacatonal* are the names that Rzedowski and Challenger use to group vegetation types with grasses as the dominant group (Challenger and Soberón, 2008, Rzedowski, 1986). In the detailed INEGI classification it corresponds to the types: Natural grassland, Halophytic grassland, High mountain prairie and savannah (Challenger and Soberón, 2008). The origins of these grassland communities is varied some are due to the climate conditions or soil conditions and others due to human disturbance and grazing (Challenger and Soberón, 2008, Rzedowski, 1986). For the High mountain prairie we will refer to Alpine and Subalpine vegetation as used by Hágsater (2005), nevertheless these communities are also known as tropical alpine (Smith and Young, 1987). Next is presented the semiarid grassland as defined by Challenger (2008). Since the Savannah and Halophytic grassland are not in the areas of our interest the description of those vegetation types are omitted.

Alpine and subalpine vegetation

Alpine grassland is the vegetation that grows above the highest tree communities on mountains. It usually grows between 3800 and 4500 m of altitude (Almeida et al., 1994, Challenger and Soberón, 2008, Hágsater et al., 2005). Subalpine vegetation refers to the communities that grow below Alpine grasslands, usually in association with open forests of *Pinus hartwegii* (Hágsater et al., 2005). Subalpine vegetation usually presents higher numbers of vascular species than alpine vegetation, but in both species associations of *Festuca* with other genera such as *Arenaria* can be found (Almeida et al., 1994). The Alpine vegetation is restricted to the higher peaks of Mexico such as the Pico de Orizaba, Popocatepetl and Iztaccihuatl. (Almeida et al., 1994). These types of vegetation area adapted to a high level of solar exposure, high temperature fluctuations and soils with low nutrients which lead to small, compact and succulent forms of growth (Almeida et al., 1994).

Subalpine communities of the Crassulaceae family comprise species such as *Sedum minimum, Villadia batesii and Echeveria secunda* (Figure 2.3.9 A and B), and can be found around 3,700 m altitude on the faces of stones on the volcano Iztaccihuatl (Clausen, 1959). With variations this subalpine communities can be associated with grasses such as *Muhlenbergia quadidentata, Calamagrostis tolucensis*, *Festuca tolucensis* and *Festuca livida,* and/or small species like

Arenaria bryoides, *Draba jorullensis* and *Oxylobus arbutifolius* and from other genera such as *Potentilla* and *Plantago* (Almeida et al., 1994, Rzedowski, 1986). Herbaceous species like *Eryngium proteiflorum*, *Luzula racemos, Senecio procumbens, Penstemom gentianoides, Cirsium* and *Lupinus montanus (Almeida et al., 1994, Rzedowski, 1986).* Some orchids like *Planthera volcanica* grow on the recent ashes of active volcanic activity (Rzedowski, 1986, Hágsater et al., 2005).

Figure 2.3.9 A) *Echeveria secunda* (Ibarra, 2013) on rocks in alpine grassland and B) Alpine grassland in skirts of Iztaccihuatl volcano (Grosselet, 2013)

Semiarid or natural grasslands

The semiarid or natural grasslands, as INEGI refers to this type of vegetation, are present in the northeast of Sonora, continuing down to the northwest of Chihuahua following the Eastern side of the Sierra Madre Occidental, down to the northeast of Jalisco on the Mexican Plateau. They are probably an extension or continuum of the grasslands of the mid-west of the United States (Burquez et al., 1998, Rzedowski, 1986). Semiarid and arid grasslands are usually in close relation with deserts-crub, thorn-scrub and oak woodlands, located between the higher altitude forests and the lower altitude scrubs between 1100 and 2500 m (Burquez et al., 1998, Rzedowski, 1986). The climate presents 300 to 600 mm of precipitation distributed between three to six months of the year. The average temperature ranges from 12 to 20°C. During winter some places can have snow, especially in the northern states (Hágsater et al., 2005, Rzedowski, 1986). Soils are almost neutral and usually fertile and some zones have deep soils (Rzedowski, 1986). Of particular importance in the grasslands vegetation type is Mezquital. The Mezquitales are classified by Rzedowski as part of the thorn forests, but INEGI classifies them as *shrub savanna with deciduous latifolia* (INEGI, 2011a). In general terms they are communities with dominance of the genus *Prosopis*. On deep and semi humid areas the Mezquitales grow as tree communities, while in arid zones they are short shrubs of 1 to 4 m high; in these cases sometimes in community with grasslands (Rzedowski, 1986). The combination of cold nights, moderate rainfall, occasional snow, and dry cold periods makes this vegetation tyape a possible source of useful green roof plants for both climates Cwb and Cfb.

Some of the main genera of grasses are *Bouteloua*, *Andropogon*, *Aristida*, *Erioneuron Festuca*, *Muhlenbergia*, *Setaria*, *Sporobulos, Stipa. Bouteloua gracilis* is one of the most common in unperturbed grasslands and deep soils, while in more shallow soils *Bouteloua curtipendula* (Rzedowski, 1986).

Figure 2.3.10 A) Huizachal grassland with *Acacia schaffneri* (Rzedowski, 2014) and B) *Echeveria agavoides*

Some grasslands do not have any woody species, but others can have a high number of shrubs such as *Acacia schaffneri* (community usually called Huizachal Figure 2.3.10 A), or with *Prosopis velutina, Berberis, Quercus cordifolia* etc. Other grassland communities are in association with *Yucca decipiens* or with *Opuntia streptacantha* (Rzedowski, 1986). Examples of Crassulaceae communities in grasslands are those of *Echeveria agavoides* (Figure 2.3.10 B) growing in north-facing rocky dry slopes together with species of *Hetchia, Brusera* and *Mammillaria* (Rundel et al., 1979). Their location may make them particularly well suited for the roof environment of Cwb climate.

2.3.6.4 Tropical deciduous forest

The tropical deciduous forest has a very low occurrence in our areas of interest since it is usually associated with warmer areas. Nevertheless, there are some instances of this type of vegetation in canyons and in valleys formed between mountains (Pennington, 1998). These forests have high quantities of deciduous trees that lose their leaves during the dry season, and some of them go dormant while other species change their metabolism from their leaves to their succulent stems such as *Acacia coulteri, Jathropha standleyi* and *Plumeria rubra* (Hágsater et al., 2005). The young soils of the deciduous forests vary widely and have characteristics from the mother bed rock, usually igneous, metamorphic or sedimentary, all of them presenting typically good drainage. Communities where Crassulaceae can be found are for example those where *Echeveria gudeliana* is present which also hold *Agave pachycentra, Hechtia glomerata, Mammillaria albilananta, Nopalea dejecta* and *Pereromia hterodoxa*. (Figure 2.3.11) (Véliz-Pérez and García-Mendoza, 2011). Species from these areas with the lowest minimum temperatures might be suitable for Cwb climates.

Figure 2.3.11 *Echeveria gudeliana* in tropical deciduous forest Photo(Véliz-Pérez and García-Mendoza, 2011).

2.4 Selected Crassulaceae species for green roofs in Cwb climate Case Study Mexico City

The first table (see Appendix 1) of possible species contains mainly plants of *Dudleya*, *Echeveria*, *Graptopetalum* and *Pachyphytum*, since genera such as *Lenophyllum*, *Thompsonela* and *Villadia* were not taken into account due to the slow growing of some of the species, the difficulty of finding them in collections, and the lack of aesthetic qualities of some of the species. Species from provenances with different type of vegetation to those identified as appropriate in the previous section were removed. The next filters were the habits of the plant growth such as size, formation of clusters or solitary growth, slow or fast growth, hardiness according to the literature and finally availability of plant species at botanic gardens and botanical collections. Two further lists were created Table 2.4.1 and Table 2.4.2 including some natural or garden hybrids are included due to their location in the wild, or their hardiness in the case of Cfb list. Plant collection in the field was unfortunately not part of this research due to time constraints, and for the protection of the plant populations of Mexican Crassulaceae, some of which are very small, localized, isolated and threatened (Reyes-Santiago, 2010). Some species were described from plants without collection references and their locality has never been found in the wild; nevertheless they have specific characteristics to hold a species status, such as the case of *Graptopetalum paraguayense* subsp. *paraguayense* (Meyrán-García, 2003).

Plants for Climate Cwb: Case study Mexico, City

Species	P. Zone	Vegetation Type	Location	Alt.	Light	Obs.
Echeveria coccinea	TVB	H. X. scrub-pedregal	Mexico City, Pedregal	2500 m	sun/half shade	not hardy
Echeveria derembergii	NMSO	Deciduous tropical forest	Oaxaca, Cerro Verde	1800 m	sun/half shade	not hardy
Echeveria elegans	TVB	*Pinus-Quercus* forest	Hidalgo, Mountains above Pachuca	Approx 2500 m	sun/half shade	probably hardy
Echeveria gigantea	NMSO	Deciduous tropical forest	Cerro de la yerba	no data	sun/half shade	not hardy
Echeveria pringley var. *parva*	MP	Deciduous tropical forest /*Pinus-Quercus* forest	Near Tayaltita, Durango	1305 m	sun/half shade	not hardy
Echeveria prolifica	TVB	*Pinus-Quercus* forest	Hidalgo, Puebla	no data	sun/half shade	not hardy
Echeveria pulvinata	NMSO	Deciduous tropical forest / *Pinus-Quercus* forest	Tomellin Canyon, Oaxaca	900 m	sun/half shade	not hardy
Echeveria shaviana	SMO	*Pinus-Quercus* forest	Dulces Nombres, Nuevo León	1800 m	sun/half shade	not hardy
Graptopetalum paraguayense	SMO	no data	probably Tamaulipas	no data	sun/half shade	hardy
Graptopetalum superbum	TVB	Deciduous tropical forest	La Barca, Jalisco	no data	sun/half shade	not hardy
Pachyphytum fittkaui	MP	Grassland	Near, Balneario de Lourdes, San Luis Potosí	1700 m	sun/half shade	no data
Pachyphytum hookeri	SMOC	*Pinus-Quercus* forest	Sierra Fría, Aguascalientes	2500 m	sun/half shade	no data
Pachyphytum werdermannii	SMO	W. X. scrub - piedmont	Jaumave, Tamaulipas	700 m	sun/half shade	no data
Sedum allantoides	NMSO	S. X. scrub (sacrocaule)	Huajapan, Oaxaca	1900 m	sun/half shade	not hardy
Sedum allantoides goldii	MP	N. Grassland (mezquital)	Ixmiquilipan, Hidalgo	no data	sun/half shade	not hardy
Sedum confusum	TVB	S. X. scrub (rosette)	Chignahuapan, Puebla	no data		half hardy
Sedum griseum	TVB	*Pinus-Quercus* forest	Valle de Bravo, Estado de México	1800 m	sun/half shade	not hardy
Sedum hernandezii	TVB	*Quercus-Pinus* forest	Sierra Negra, Puebla	2400 m	sun/half shade	probably hardy
Sedum jurgensenii v. *alongata*	TVB	*Quercus-Pinus* forest	Jacala, Hidalgo	1650 m	sun/half shade	little bit leggy
Sedum mexicanum	no data	no data	No data	no data	half shade	half hardy
Sedum nussbaumerianum	TVB	Deciduous tropical forest	Mpio. Puente Nacional, Ver	450 m	sun/half shade	not hardy
Sedum oaxacanum	SMNO/ TVB	Deciduous tropical forest / *Quercus-Pinus* forest	Cerro de la Yerba, Puebla	no data	no data	not hardy
Sedum oxypetalum	TVB	H. X. scrub-pedregal	Pedregal, México, D.F.	2500 m	sun/half shade	not hardy
Sedum pachyphyllum	SMNO	Deciduous tropical forest	Near San Luis Atolotitlan, in Oaxaca	1800 – 2100 m	sun/half shade	not hardy
Sedum stahlii	TVB	S. X. scrub (rosette)	Cumbres de Alcutzingo Veracruz	no data	sun	almost hardy
Sedum palmeri ssp. *emarginatum*	TVB	*Quercus-Pinus* forest	Peña del aire, near Hueyapan, Hidalgo	1960 m	sun/half shade	perhaps hardy

Sedum luteoviride	x	TVB	*Pinus*-*Quercus* forest	natural hybrid San Vicente, Hidalgo	no data	sun/half shade	half-hardy
Sedum rubrotinctum	x	non	non	Garden hybrid *S. stahlii* and *S. pachyphyllum*	no data	sun/half shade	half-hardy

Table 2.4.1 Potential species for green roofs in Climate Cwb based on (Almeida et al., 1994, Bischofberger 2010, Burquez et al., 1998, Canizales-Velázquez et al., 2009, Castillo-Argüero et al., 2004, Clausen, 1959, Eggli, 2003, Etter and Kristen, 1997, Evans, 1962, Evans, 1983, García-Morales, 2013, González-Medrano, 2004, Hágsater et al., 2005, INEGI, 2011b, INEGI, 2011a, Kimnach Myron, 1986, Leopold, 1950, Low, 2008, Low, 2007a, Low, 2007b, Low, 2007c, McDonald, 1990, Meyrán-García, 2003, Miranda and Hernández, 1963, Pilbeam, 2008, Praeger, 1921, Rzedowski et al., 2010, Rzedowski, 1986, Sánchez-Del Pino et al., 1999, Stephenson, 1994, Stromberg, 1993, t'Hart, 1997, Thiede and Eggli, 2007, Véliz-Pérez and García-Mendoza, 2011, Walther, 1952). In the column observations the hardiness report for *Sedum, Graptopetalum* and *Graptoveria* are reports from Ray Stephenson for Northumberland, UK. *Echeveria* species hardiness based on reports by Pilbeam for the UK. Non data on the altitude column means it was not found of records in literature and first descriptions of the plant species.

Plants for Climate Cfb: Case study Sheffield, UK

Species	Phys. Zone	Vegetation Type	Location	Altitude	Light	Obs.
Echeveria agavoides	MP	N. Grassland	Villa de Arraiga, SLP	no data	sun/half shade	not hardy
Echeveria elegans	TVB	*Pinus-Quercus*	Hidalgo, near Pachuca	App. 2500 m	sun/half shade	probably hardy
Echeveria prolifica	TVB	*Pinus-Quercus* forest	Hidalgo, Puebla	no data	sun/half shade	not hardy
Echeveria secunda	TVB	*Alpine and subalpine grassland*	Popocatepetl	3980 m	sun/half shade	probably hardy
Echeveria strictiflora	SMO	*Pinus-Quercus* forest	Dulces Nombres, Nuevo León	no data	sun/half shade	probably hardy
Graptopetalum paraguayense	SMO	no data	probably Tamaulipas	no data	sun/half shade	hardy
Graptopetalum paraguayense ssp. *bernalense*	SMO	no data	Tamaulipas	700-800 m	sun/half shade	hardy
Pachyphytum compactum	MP	N. Grassland (mezquital)	Near Colón, Querétaro	2100 m	sun/half shade	Probably hardy
Pachyphytum glutinicaule	MP	N. Grassland (mezquital)	Near Ixmiquilpan, Hidalgo	1550 m	sun/half shade	half hardy
Pachyphytum werdermannii	SMO	W. X. scrub - piedmont	Jaumave, Tamaulipas	700 m	sun/half shade	no data
Sedum australe		No data	Guatemala	No data	No data	no data
Sedum confusum "Cerro de la Yerba"	TVB	S. X. scrub (rosette)	Chignahuapan, Puebla	no data	no data	half hardy
S. confusum “Large Form”						
Sedum commixtum	NMSO	*Alpine and subalpine grassland*	Santo Domingo, Ozolotepec, Oaxaca	*2600*	sun/half shade	hardy if dry
Sedum griseum	TVB	*Pinus-Quercus* forest	Valle de Bravo, Estado de México	App. 1800 m	sun/half shade	not hardy
Sedum hernandezii	TVB	*Quercus-Pinus* forest	Sierra Negra, Puebla	2400 m	sun/half shade	probably hardy
Sedum hultenii	SMO	*Quercus-Pinus* forest	Near Texcapa, Puebla	1300 m	sun/half shade	probably hardy
Sedum lucidum	TVB	*Quercus-Pinus* forest	Near Orizaba, Veracruz	no data	sun/half shade	probably hardy
Sedum mexicanum	no data	no data	No data	no data	half shade	half hardy
Sedum moranense 138	TVB	*Quercus-Pinus* forest	Near las Vigas, Veracruz	no data	sun/half shade	probably hardy
Sedum moranense C4	no data	no data	no data	no data	no data	no data
Sedum moranense C7	no data	no data	no data	no data	no data	no data
Sedum moranense nursery	no data	no data	no data	no data	no data	no data
Sedum palmeri Clone *1*	no data	no data	no data	no data	no data	no data
Sedum palmeri Clone *3*	no data	no data	no data	no data	no data	no data
Sedum palmeri ssp. *rubromarginatum*	MP	S. X. scrub (sacrocaule)	El Ranchito, near Villa de Zaragoza, SLP	2100 m	sun/half shade	perhaps hardy
Sedum dendroideum ssp. *praealtum*	SMO	*Pinus-Quercus* forest	Near Río Blanco, Veracruz	no data	sun/half shade	probably hardy
Sedum reptans	MP	*Quercus-Pinus* forest	Cerro Agujón, SLP	1700 m	sun/half shade	probably hardy
Sedum stahlii	TVB	S. X. scrub (rossette)	Cumbres de Alcutzingo Veracruz	no data	sun	almost hardy
Sedum x 'Rockery challenger'	non	non	*S. sarmentosum* *Sedum mexicanum*	no data	sun/half shade	probably hardy
Sedum x 'Spiral stairs'	non	non	Probably *S. moranense* and another species	no data	sun/half shade	probably hardy
Sedum x *luteoviride*	TVB	*Pinus-Quercus* forest	natural hybrid San Vicente, Hidalgo	no data	sun/half shade	probably hardy
x *Graptoverya 'aucalis'*	non	non	*G. paraguayense* x *Echeveria amoena*	no data	sun/half shade	probably hardy

Table 2.4.2 Potential plants for roofs in climate Cfb, based on (Almeida et al., 1994, Bischofberger 2010, Burquez et al., 1998, Canizales-Velázquez et al., 2009, Castillo-Argüero et al., 2004, Clausen, 1959, Eggli, 2003, Etter and Kristen, 1997, Evans, 1962, Evans, 1983, García-Morales, 2013, González-Medrano, 2004, Hágsater et al., 2005, INEGI, 2011b, INEGI, 2011a, Kimnach Myron, 1986, Leopold, 1950, Low, 2008, Low, 2007a, Low,

2007b, Low, 2007c, McDonald, 1990, Meyrán-García, 2003, Miranda and Hernández, 1963, Pilbeam, 2008, Praeger, 1921, Rzedowski et al., 2010, Rzedowski, 1986, Sánchez-Del Pino et al., 1999, Stephenson, 1994, Stromberg, 1993, t'Hart, 1997, Thiede and Eggli, 2007, Véliz-Pérez and García-Mendoza, 2011, Walther, 1952). In the column observations the hardiness report for *Sedum, Graptopetalum* and *Graptoveria* are reports from Ray Stephenson for Northumberland, UK. *Echeveria* species hardiness based on reports by Pilbeam for the UK. *Non data* on the altitude column means it was not found of records in literature and first descriptions of the plant species.

2.5 Conclusions

The general methodology for plant selection using the Köppen-Geiger-Kottek world climatic map, and the incorporation of further climatic parameters, provided a long-list of possible candidate Mexican Crassulaceae species for green roofs in the Cwb and the Cfb climates. The further addition of multiple layers of information, such as the type of habitat of the climatic and physiographic zones, helped as a thinning criterion for the first list of potential species, thereby narrowing the selection to the best candidates. The first long-lists can be consulted in the Appendix 1. Some species of the initial list that were not used in the present study might be worthy of testing if they provide a particular interest in terms of biodiversity, especially within Mexico. Other species might be highly desirable to use due to their aesthetic value, but the major limiting factor in the final list selection was the availability of plant species material, they have to become more easily available through botanic collections. If a more concerted effort to expand the green roof palette is to be made.

In the proceeding chapters, the methodologies and results of experiments and screenings of the carefully selected species for each climate are presented. For the Cwb climate the experiments were performed in Mexico City, while for the Cfb climate, experiments were conducted in the city of Sheffield in the UK. The final success of the plant methodology selection across these experiments and study sties is discussed in the conclusions in relation to the performance of the selected species in their respective climate.

Chapter 3 Testing Mexican *Sedum* in climate Cwb: Mexico City

3.1 Introduction

In Chapter, 2 a plant selection methodology was developed and several species of Crassulaceae were identified as candidates suitable for testing on green roofs of the climate Cwb (**warm temperate with dry winter and warm summer**) of the Köppen-Geiger-Kottek Climate classification. Following on from the formulation of this group of target species, Chapter 3 to responds to three main questions.

1) Which is the optimal planting season for the establishment of Mexican *Sedum* species in the Cwb climate?
2) Which is the optimal substrate depth for the growth of Mexican *Sedum* species in the Cwb climate in terms of plant performance?
3) Which of the selected Mexican *Sedum* species selected for this study have the best performance on green roofs in the Cwb climate?

To answer these questions an experiment with ten *Sedum* species was set up in Mexico City. The location of the experiment was on the roof of the offices of the Botanical Garden of the UNAM (National Autonomous University of Mexico). This chapter presents the results of the experiment separated into two sections: **Section 3.3** presents the data comparing the effect of **two planting seasons and three depths** on initial establishment and survival up to **day 280** of the experiment. **Section 3.4** presents plant response data at **three depths** only for those plants established during the **wet planting** season over the extended period of **460 days**.

The experiments were structured in the above way due time restrictions and minimal resources. It was decided that the duration of the **dry season planting** experiment would continue for enough days for the plants to experience the initial drought conditions and the onset of the later wet conditions. Those plants established in the wet season, however, were **left to grow for 460** days to obtain data **from two growing seasons**. In this way, two data sets were explored: Two planting seasons and three depths each comprising 280 days, and the complete dataset of the 460 days of the wet season (Figure 3.1.1).

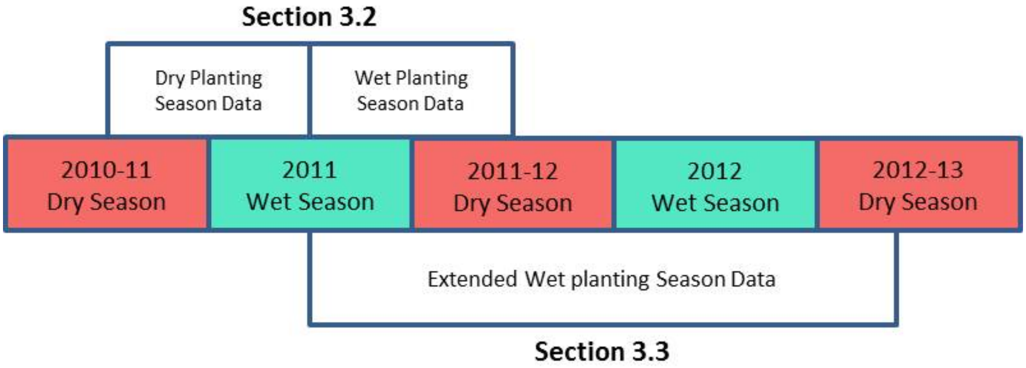


Figure 3.1.1 Scheme of the experimental planting season and data presented in the following sections of this chapter

3.1.1 Ten *Sedum* species in Cwb climate: effects of planting season and substrate depth

3.1.1.1 Substrate Depth

The rhizosphere, the below-ground environment of the plant, is a critical zone for plant health. The soil, or substrate in which the plant is grown, provides the plant with all macro- and micro-nutrients, beneficial biota such as probiotic bacteria and mycorhizza, and is the interface whereby the plant obtains all its water necessary for survival. The green roof, by its very location, has limitations: the structure can only carry a minimal weight of substrate; that substrate can only hold a finite amount of water; and the exposure of the substrate to the wind and temperature fluctuations creates a stressful growth environment. Research on the effects of substrate depth on survival, growth and performance of plants, summarised below, has often been approached using different methodologies with different aims.

The smaller the volume of substrate, the lower its capacity to hold heat. The shallower the substrate the more easily it is affected by frost. Boivin (2001) analysed the effect of substrate depth on freezing injury of plants growing on roofs in Canada and found that a minimum of 100 mm depth helps to reduce the freezing injury of plants. This is probably due to the substrate ability of buffering temperature fluctuations. Hauth and Liptan (2003) setup and experiment in Portland (U.S.) comparing substrate depths and irrigation regimes. On the east side of a roof, with only three inches of substrate, and irrigated with six inches of water in the summer of 2001 and three inches in the summer of 2002. Whereas the west side, with five inches of substrate, was irrigated with 4 and 2 inches of water during the summers of 2001 and 2012, respectively. The roof was planted with pre-germinated mats, plugs of succulents and perennials, a hydro-seed matrix of perennial flowers and grasses and a small area with native grasses and wildflowers. The authors observed a higher colonization of weeds on the deeper substrate and a greater requirement for irrigation was obtained for some species, such as *Thymus*.

Dunnett and Nolan (2004) tested the effect of 100 mm and 200 mm substrate depth and additional watering on 9 herbaceous perennials. They showed that the increase of substrate depth alone had no significant effect on plant performance. Nevertheless, some plants displayed longer flowering periods when grown in the deeper substrates. The additional watering treatment resulted in the most significant increases in plant performance, especially at the 100 mm depth, with the exception of low growing species like *Sedum acre* which presented poorer performance at the 100 mm depth with extra watering (Dunnett and Nolan, 2004). In contrast, Dunnett and Nagase (2008b), analysing the same experiment extended over five growing seasons, found greater plant survival at the 200 mm depth, as well as higher total biomass production, flowering, species richness, and diversity (2008b). These results attest to the importance of longer term experiments and the limitations of short term projects. Nevertheless, due to space constraints, budget, and other factors, many studies have to be of shorter duration, and the Cwb and Cfb works presented here derive from a relatively short term study.

Van Woert et al. (2005) set up a greenhouse experiment to test the performance of a mix of seven *Sedum* species in three substrates: a 2 cm depth; 2 cm depth + an extra moisture retention fabric layer; and a 6 cm depth. These depth treatments were in combination with five watering regimes: 2, 7, 14, 28 and 88 days between watering. In this case, the 6 cm substrate presented the best performance in moisture retention and plant growth since the 6 cm substrate took longer to dry and a higher amount of water was available for the plants during drought (Van Woert et al., 2005).

Mexican species' survival responses with different substrate depths and temperatures has been explored, in part, by Durhman (2007) who tested 25 species on green roofs in three depths (25 mm, 50 mm and 75 mm) in Michigan. None of the ten Mexican species or Mexican hybrids survived to the end of the experiment across all depth treatments (Durhman et al., 2007). The total mortality is not surprising, considering the species were subjected to temperatures below -20°C, never experienced by the selected Mexican species in their native habitats. On the other hand, the non-Mexican species showed a higher survival and fastest growth rates in the deeper substrates. The above example stresses the necessity of testing species in climates homologous or similar to that of their native habitat.

Thuring et al. (2010) found that early drought combined with shallow substrates can reduce growth, particularly in herbaceous species. In this study, herbaceous species were more affected by the interaction of depth and drought, while stonecrops were mainly affected by depth and in general plants grown in deeper substrates had higher biomass than plants in shallower substrate (2010).

Substrate depth is one of the main factors affecting wild plant diversity on green roofs. Madre et al. (2014) performed a wild plant survey on 115 roofs ranging from extensive to simple-intensive (40 to 200 mm and 120 to 1000 mm), according to the FLL classification (FLL, 2008).

Taxonomic composition of wild plant communities on green roofs was determine by depth and age of the roof (i.e. time since establishment), whereas functional composition of the wild plant communities was driven by depth and maintenance intensity (Madre et al., 2014).

Another important factor in species composition is solar radiation, which in combination with substrate depth can also affect the diversity of species on the roof. Getter et al. (2009) observed the effect of solar radiation (full sun and full shade) and substrate depth (80 and 120 mm) on the absolute cover of nine species, plant stress responses, plant community development, and substrate moisture. In the shaded plots *S. acre* become the dominant species at both depths, followed by *Allium cernuum, Sedum album* and *Talinum calycinum*. In contrast, for full sun plots, both depths had a higher abundance of *S. album*, *T. calycinum* and *S. acre* and in this case *Allium cernuum* was less abundant than in the shaded plots. Nevertheless*,* for the pooled species, solar radiation and depth did not have an effect on overall absolute cover. Volumetric moisture content was not affected by solar radiation at the 80 mm depth, but in the 120 mm depth it was higher in the shade. It is evident that the species composition on the roofs will change depending on the microclimates generated by factors such as shade, substrate depth, and moisture content, and in the most stressful environments *Sedum* species tend to dominate. This situation requires us to find different species of *Sedum* and/or other *Crassulaceae* species for the green roof, to avoid the use of the same species in all roofs and to identify similarly successful plants that can add diversity and potentially greater services existing systems.

To analyse the role of substrate components on plant growth and physiological performance on green roofs. Young (2014) performed an experiment in a temperature controlled green house with a regime of 16 h days at 20 °C and 8 h nights at 15 °C during five months. Substrate depth, of 80 and 120 mm was analysed and pots were watered with 150 ml of water per week. In this experiment substrate depth did not appear to provide any substantial improvement to the plant growth. This was perhaps due to the controlled environment where the plants did not suffer extremes of drought, heat or solar radiation.

In 1994 M. Siemsen set up perhaps the first green roof study in Mexico (Grau et al., 2005) at the University of Chapingo. He tested three different substrate compositions with a gradual increment in depths from 25 to 70 mm (Grau et al., 2005). Unfortunately, the results of this research have not been published yet.

The above examples demonstrate the critical effect of substrate depth on plant survival. Depending on the climate, substrate depth protects the plants either from cold or drought. In the case of low temperatures substrate depth works as insulation for the plant roots (Boivin et al., 2001), while in dry conditions, the deeper the substrate the higher retention of moisture below the surface level. The shallower the substrate depth, the faster the substrate dries. Consequently, with greater substrate depth the planting choices available, the vegetation palette, expands and the environmental services also increases. For example, the ‘deeper’ green roof will be able support larger species, which require a more extensive rhizosphere, and furthermore, the more diverse the palette, the more likely that those plants will provide more invertebrate habitats and vertebrate food sources. They will exhibit longer flowering periods which in turn increase nectar and pollen production for bees (Brenneisen, 2005). The choice of depth, therefore, is a strong determinant of plant and community ‘fate’ –whether it dies or thrives- in the green roof, environment.

3.1.2 Planting season

The planting season can also have a significant impact on the establishment success of plants on the roof. This planting season may vary depending on location, plant type, and substrate depth and composition. For this reason, careful research is required before embarking on a new planting project in order to minimise mortality, which could be very costly, both economically and in terms of time and resources. Getter and Rowe (2007) found that almost all of eight *Sedum* species plugs that they had planted in spring had significantly higher survival than plugs planted during the fall in Michigan. Their trial, however, suggested that depth (40, 70 and 100 mm) had no effect on survival in their design (Getter and Rowe, 2007). (2007). In this study, planting season was found to be critical in terms of plants’ tolerance to cold, and the number of weeks they had to produce deeper and more extensive roots before the arrival of cold weather was a matter of life and death. In other cases like the Cwb (warm temperature with dry winter and warm summer) climates, the planting season might exacerbate other plant stressors such as drought, and flooding, or high irradiance and shade.

3.1.3 Objectives

The main objectives of this experiment are to determine the optimal substrate depths and planting season times for 10 species of Mexican *Sedum* candidates identified in Chapter II. Specifically, two different planting seasons -dry and wet- and three different substrate depths -50, 100 and 150 mm- are compared.

3.1.4 Methods and materials

The experiment was set up on the roof of one of the buildings of the Institute of Biology of the National Autonomous University of Mexico. The plots were oriented towards the North, with no buildings or trees to shade them; hence plants were exposed to the light during the entire day. The experiment consisted of three beds of 1.20 x 0.60 m area and of 50, 100 and 150 mm depth, with three replications, and therefore a total of nine beds. Each bed was made up of pine wood frames. The frames were built with 20 mm thick planks, and were 75, 125 or 175 mm in height in order to hold the substrate plus 20 mm for drainage and 5 mm for filter sheets and a root barrier. Each frame was placed directly on the surface of the roof. A 2 mm anti-root membrane was placed inside the frame in direct contact with the floor. The 4 planks of each frame and the root barrier sheet had a total of 10 holes of 25 mm diameter for drainage on the edge corner between the roof surface and the planks. On top of the root barrier sheet was a 1 mm protective sheet, a 20 mm drainage layer of dust-free white volcanic rock, and a 1 mm filter sheet on top. The filter sheet, protective sheet and root barrier were supplied by *Geoproductos de México* (Figure 3.1.2). The beds were categorised in order of 50, 100, and 150 mm for the three replicates, and this design was considered in the data analysis.

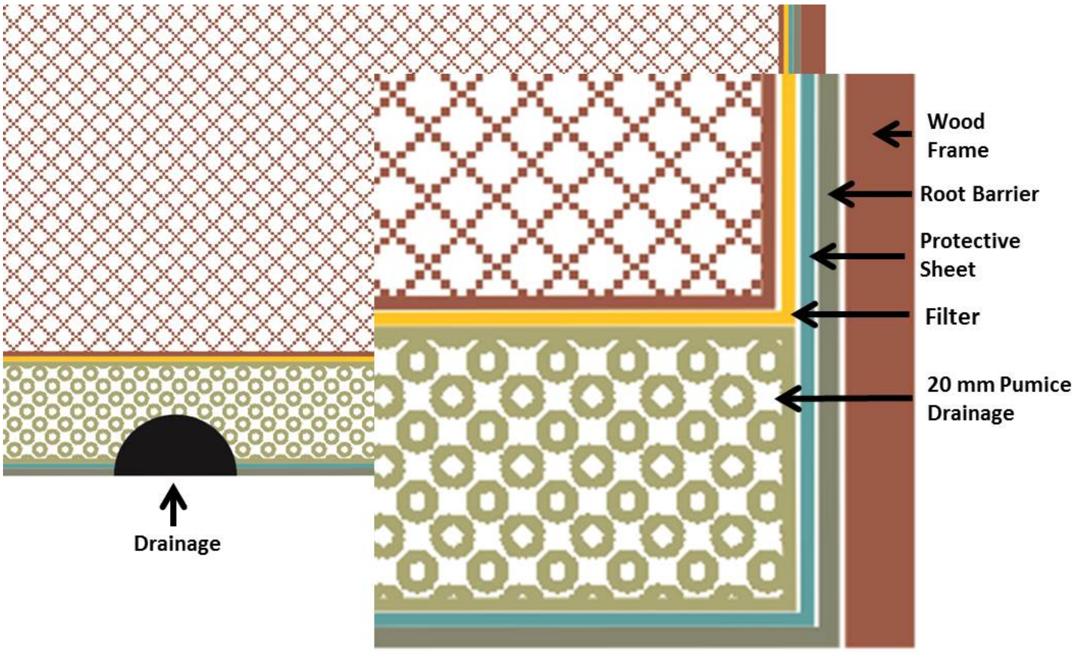


Figure 3.1.2 Detail of layers of experimental grow units

Each bed was filled with 50, 100 or 150 mm of substrate (Figure 3.1.3). The substrate was mixed on site, comprising 60% pumice rock and 40% garden waste compost. Both pumice rock and compost were sieved on a 10 mm grid. The compost was donated by the composting facility of the National Polytechnic Institute, Mexico City. The pumice was bought from suppliers *Jardines Flotantes* in the Xochimilco delegation in Mexico City. No shading was projected from the bed frames to the plants.

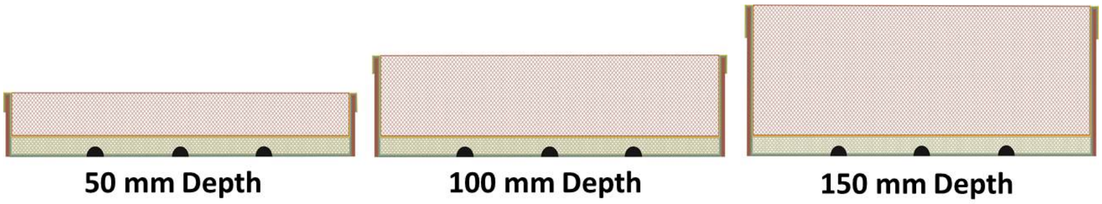


Figure 3.1.3 Cross section of 50 mm, 100 mm and 150 mm depth plots

The plants were propagated and donated by and at the installations of the National Crassulaceae Collection at the Botanic Garden of the Autonomous National University of Mexico. Each bed was planted with five un-rooted cuttings per species (with ten species in total) (Table 3.1.1), randomly distributed in a 100 x 100 mm grid, with a total of 50 plants per plot. All cuttings consisted of a single 140 mm long shoot. The cuttings were taken from mother plants that were growing under direct sun light at ground level. All cuttings were prepared by removing all their leaves from half way down the stem and were left to heal for three days in baskets under half shade to avoid infections when planted. This process was the same for the two planting seasons.

For the dry season establishment experiment, cuttings were planted on the roof in October 2010, at the end of the rainy season. Plants were watered every other day for one week and twice a week for the first month of establishment, until water was observed draining from underneath the plots. During days with sufficient rain to saturate the plots, beds were not watered. During the second month, plants were watered once every two weeks only if there was no rain. In the third month the plants were watered twice more. No supplementary water was provided after that period, except during episodes of extreme drought.

For the rainy season establishment experiment cuttings, were planted on the roof in July 2011, in the first third of the rainy season. These cuttings were not watered during establishment. Due to the constant saturation of the substrate during establishment, because of the high levels of precipitation, some cutting started to develop signs of fungal infection; and therefore an antifungal treatment was applied on day 40 to all plants. After establishment, only at days 140 and 180, the 'rainy season' plants were provided with enough emergency supplemented water until it was observed draining from underneath the plots. This was because they had reached the height of dry season and were affected by the extreme drought.

3.1.5 Selected species

For the experiment described in this Chapter (3), 10 *Sedum* species were selected from the plants identified in Chapter II as candidates for growth in Cwb climates (Table 3.1.1 and Figure 3.1.4 A-J). The majority are native to the Transverse Neovolcanic Belt and the Northern Mountain Range of Oaxaca. Some of the species have been used previously on green roofs, but no Mexican research has been published to date concerning their responses and there is no available data or characterization of the species for Cwb climates. Since some of the listed species are known to survive on Cwb roofs, the performance of these species under different conditions can shed light on the basic requirements for the optimal establishment strategy of Crassulaceae species on roofs in a Cwb climate. This will be particularly important for cases like Mexico, where the preferred planting method is by the use of un-rooted cuttings due to the easier transportation of the plants to the roof.

Species List For This Study

Species	Plant Form	Height	Foliage colour	Flower colour	P. zone	Altitude range	Vegetation Type
S. allantoides	Subshrub	20-30 cm	Pale green	White	NMSO	1900 to 2100 m	W. X. scrub microfilous
S. allantoides 'Goldii'	Subshrub	20-30 cm	Pale green	White	NMSO	1900 to 2100 m	N. Grassland (mezquital)
S. confusum (prob. Large Form)	Subshrub	8-20 cm	Dark green	Yellow	TVB	No data	No data
S. griseum	Subshrub	14-18 cm	Grey-green	White	TVB	aprox 1800	Pinus-Quercus forest
S. jurgensenii ssp. *jurgensenii*	Subshrub	15 to 20 cm	Light green	White	TVB	1100-2500	H. X. scrub-pedregal
S. x *luteoviride*	Subshrub	10 cm	Bright green	Yellow	TVB	No data	No data
S. mexicanum	Ground cover	6 to 8 cm	Bright green	Yellow	No data	No data	No data
S. oxypetalum	Subshrub	1 m	Dark green	White	TVB	2500	H. X. scrub-pedregal
S. x *rubrotinctum*	Subshrub	30 to 30 cm	Green and bright red	Yellow	No data	No data	No data
S. stahlii	Subshrub	18 to 20 cm	Brown-red	Yellow	TVB	2500	S. X. scrub

Table 3.1.1 List of species used for this study in two planting season experiment and three substrate depths. Based on (Eggli, 2003, Etter and Kristen, 1997, Evans, 1983, García-Morales, 2013, Meyrán-García, 2003, Pilbeam, 2008, Praeger, 1921, Stephenson, 1994). *Non data* on the altitude column means it was not found of records in literature and first descriptions of the plant species.


A) *Sedum allantoides*


B) *Sedum allantoides* 'Goldii'


C) *Sedum confusum*


D) *Sedum griseum*


E) *Sedum jurgensenii*


F) *Sedum* x *luteoviride*

G) *Sedum mexicanum* **H)** *Sedum oxypetalum* **I)** *Sedum* x *rubrotinctum*

J) *Sedum stahlii*

Figure 3.1.4 A) *Sedum allantoides,* B) *Sedum allantoides* Goldii ,C) *Sedum confusum,* D) *Sedum griseum,* E) *Sedum jurgensenii,* F) *Sedum* x *luteoviride,* G) *Sedum mexicanum,* H) *Sedum oxypetalum,* I) *Sedum* x *rubrotinctum,* J) *Sedum stahlii*

3.1.6 Data collection

For the dry planting season plants, measurements of long and short diameters, plant height, and individual survival were recorded from the beginning of the experiment, on day 120, day 240 and day 280 when the plants were harvested. Unfortunately for the dry season experiment, final biomass was not recorded due to lack of available facilities to dry and weigh the plants at the time. For the wet planting season it was possible to record the same measurements monthly until day 460. At the end of the wet-planting season, the plants were harvested, shoots and roots were divided, roots were washed, and all material was oven dried at 70° C for three days or more, depending on weight stability, prior to weigh final dry biomass. Ambient temperature and precipitation data were collected from the National Meteorological Service (SMN-México, 2014). This section presents the data collected for both planting seasons up to day 280, while Section 3.3 presents the complete monthly data of the wet planting season.

3.1.7 Data analysis

As mentioned in this chapter's introduction, the results of the planting season and substrate depth experiment will be presented in this chapter in two different sections: Section 3.3 presents the results, discussion and conclusions of the experimental design to evaluate the performance of the ten *Sedum* species planted in three different depths, comparing two different planting seasons until day 280. Section 3.4 presents detailed analysis of the complete dataset of the summer planting season plots, which were run for 460 days (Figure 3.1.5). The data analysis was therefore split into two parts:

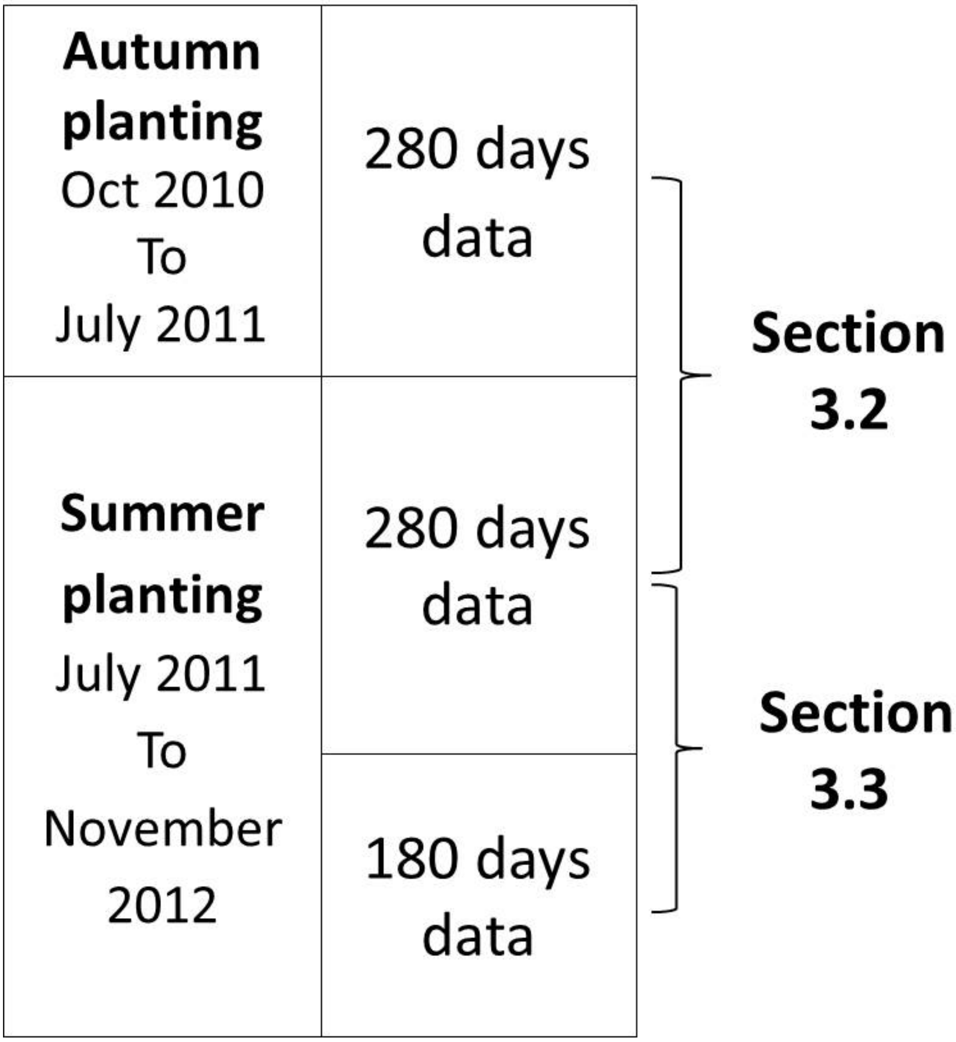


Figure 3.1.5 Chapter and analysis structure

3.1.7.1 Data analysis of two planting seasons and three substrate depths

For the survival data of the *season-depth* experiment, the percentage survival was first analysed for day 280, when the dry season plants were harvested. For this set the statistical analysis was performed with the package R Studio version 3.0.1. (R Development Core Team, 2013). Data were transformed using arcsine square root transformation. A generalized linear model was applied first with function glm for the general contrast. Planting season was a factor with depth nested, and species as an explanatory variable. Poisson error was used to analyse the proportional data (Crawley, 2005). A further Tukey HSD comparison of means for linear models was applied with *Multcomp* package for R (Hothorn et al., 2008) for the main factors.

The means of the long and short diameters of the plants from season-depth experiment were analysed first for the day 280, when the dry season plants were harvested. All data were transformed ($\log_e + 1$). The statistical analysis was performed with R Studio version 3.0.1. (R Development Core Team, 2013). For this set of data, a one way nested ANOVA test was applied with the model: season/depth/species. Further multiple comparisons of means were obtained using Tukey HSD.

Survival percentage repeated measures data were transformed with arcsine square root and analysed with a general linear model for repeated measures. Season and depth were used as factors and species were nested in factor depth. In the cases in which the assumption of sphericity of the data was violated, a Greenhouse-Geisser correction for ($\varepsilon < 0.75$) or Huynd-Feldt ($\varepsilon > 0.75$) was applied. Diameters and height data were transformed ($\log_e + 1$). With diameters, height, and relative growth rate, the same general linear model for repeated measures was applied with package SPSS. Due to the structure of the experiment the analysis was performed as a nested design with the following form: Season/depth/species. The same corrections were used in case of violation of the sphericity assumption. The non-destructive RGR measurement was selected in order to have a proxy measurement of the growth of individual plants relative to their initial size. Although destructive method could have ben used this was avoided due the limited amount of space and plant material, and because a destructive method would have not account for the area used by the plants, which is an important element when analysing plant species on green roofs.

The diameter relative growth rate was calculated with the following formula:

$$\text{RGR} = [\log_e(\text{Diameter 2}) - \log_e(\text{Diameter1})]/t2 - t1 \text{ (Hunt, 1990).}$$

RGR = Relative growth rate
$\log_e$= Natural logarithm
Diameter 1= Initial mean diameter
Diameter 2= Subsequent diameter
t1= Initial time in days
t2= Subsequent time in days

The RGR dataset was analysed with a Multivariate Test. All the graphs displayed below show back transformed data for the readers easier interpretation and understanding of the system. An alpha level of 0.05 was used for all statistical tests.

3.1.7.2 Data analysis of three substrate depths

For the survival data of the *three depths* experiment, the repeated measures of survival percentage data were transformed with arcsine square root and analysed with a general linear model for repeated measures. Depth was set as factor and species were nested in depth. The correction of sphericity of the data due to the within measures, was corrected with the Greenhouse-Geisser correction for ($\varepsilon < 0.75$) or Huynd-Feldt ($\varepsilon > 0.75$). For diameters, height data was transformed with the natural logarithm. Diameters, height and relative growth rate (RGR) were analysed with the same general linear model for repeated measures applied with package SPSS. Depth was set as factor and species were nested in depth (Depth/species). To correct the sphericity of the data of the repeated measures of diameters and height, the Greenhouse-Geisser correction for ($\varepsilon < 0.75$) or Huynd-Feldt ($\varepsilon > 0.75$) were used. The diameter relative growth rate was calculated using the same formula as above.

All graphs presented are back transformed, with the exception of the relative growth rate (RGR). A Kendall rank correlation test was applied to the RGR and the rainfall data since distribution was non-parametric. The percentage cover was transformed with arc-sine transformation and analysed with a one-way nested ANOVA. Depth was set as factor and species were nested in depth (Depth/species). An alpha level of 0.05 was used for all statistical tests.

3.2 Results for the 10 *Sedum* species, 2 planting season and 3 substrate depths

This section presents the individual results of all the 10 *Sedum* species in the **two planting** seasons and **three substrate depths**. The first section describes the patterns in temperature and precipitation experienced by the plants during the experiment. The second section details the results for each individual species (i.e. survival, diameter relative growth rate, height and diameter). Finally, the third section presents and discusses the overall results of the model.

3.2.1 Temperature and precipitation

The **dry planting season** experiment was set up in October of 2010 and ran for a total of ten months and two weeks, at which time the plots were cleared and prepared for the wet planting season experiment.

During those months the mean precipitation was 44.22 mm and the total accumulated precipitation was 442.2 mm (Figure 3.2.1 A). The months of December and January (Days 60-90) had the lowest amount of rain with 0.1 mm, and the month with the highest amount of rain was July with 230.5 mm (Day 280), at the end of the experiment (Figure 3.2.1 A). The mean temperature was 17.12 °C (Figure 3.2.1 B), the mean minimum temperature was 9.80 °C, and the mean maximum temperature was 24.35 °C. December had the lowest mean minimum temperature of 4.91 °C (Day 60) and June had the highest mean maximum temperature of 28.71 °C (Day 210) (Figure 3.2.1 B).

The **wet season** experiment was initiated at the second week of July 2011 and the plants were harvested in the third week of November of 2012. However, for the purpose of the comparison of the two planting seasons, this section considers the non-destructive dataset up to the month of May 2012. This allows comparison of the plant growth during the same number of days for both these highly contrasting seasons. For this period the mean precipitation was 43.93 mm, and the total accumulated precipitation was 439.3 mm (Figure 3.2.1A). The month with the lowest precipitation was December with 0.91 mm (Day 150) and August had the highest rainfall with 158.90 mm (Day 1) (Figure 3.2.1 A). The mean temperature for the 10 months was 16.62 °C (Figure 3.2.1 B); the mean maximum temperature was 23.22 °C and the mean minimum temperature was of 10.05 °C. The coldest month, December (Day 150) (Figure 3.2.1 B), had a mean minimum temperature of 6.3 °C and the hottest month, May (Day 210) had a mean maximum temperature of 27.01 °C (Figure 3.2.1B).

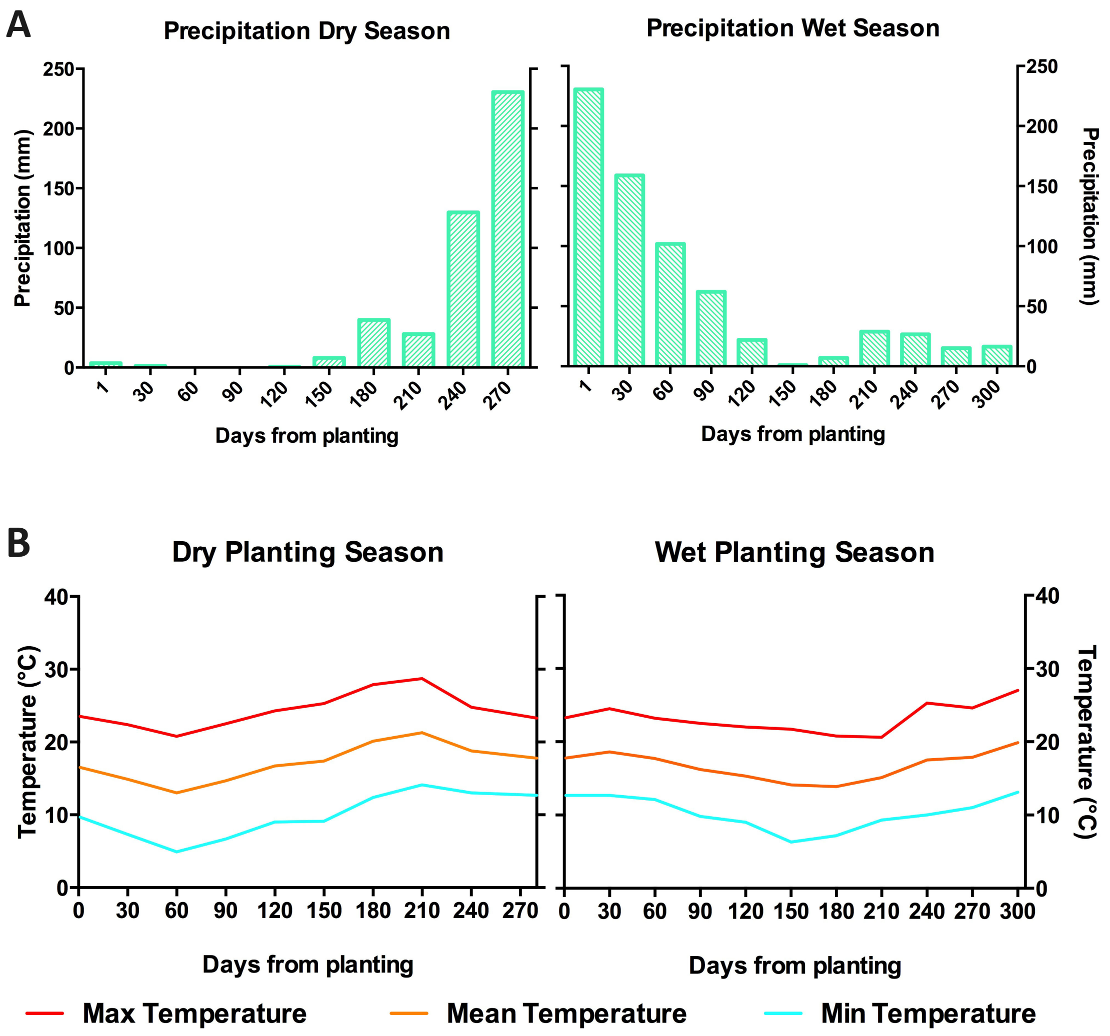


Figure 3.2.1 A) Precipitation for Dry and Wet planting season. B) Mean, maximum and minimum temperature. Graph based on data from National Meteorological Service, Mexico.

3.2.2 Results per species

3.2.2.1 *Sedum allantoides* 'Goldii'

Sedum allantoides 'Goldii' a natural genotype of species had significantly greater survival when planted during the wet season ($p<0.05$, Tukey HSD), but no significant differences in survival between depth, neither within nor between seasons ($p>0.05$, Tukey HSD) (Figure 3.2.2 A and B). Interestingly the diameter RGR was significantly higher for *S. allantoides* Goldii plants established during the dry season ($p<0.05$, Tukey HSD) (Figure 3.2.2 C and D). Furthermore following the same pattern, this species was one of only two species that achieved a significantly higher mean diameter ($p=0.008$, Tukey HSD) when planted in the dry season than in the wet season (Figure 3.2.2 E and F). This species was the only species that grew taller when established during the dry planting season ($p=0.005$, Tukey HSD) (Figure 3.2.2G and H). Possible reasons for these positive responses are that this stress tolerant species had less competition on the dry season. No differences of diameter were found between depths within or between seasons ($p>0.05$, Tukey HSD) (Figure 3.2.2 E and F). No differences in grouped responses to different depths were found ($p>0.05$, Tukey HSD) (Figure 3.2.2 G and H).

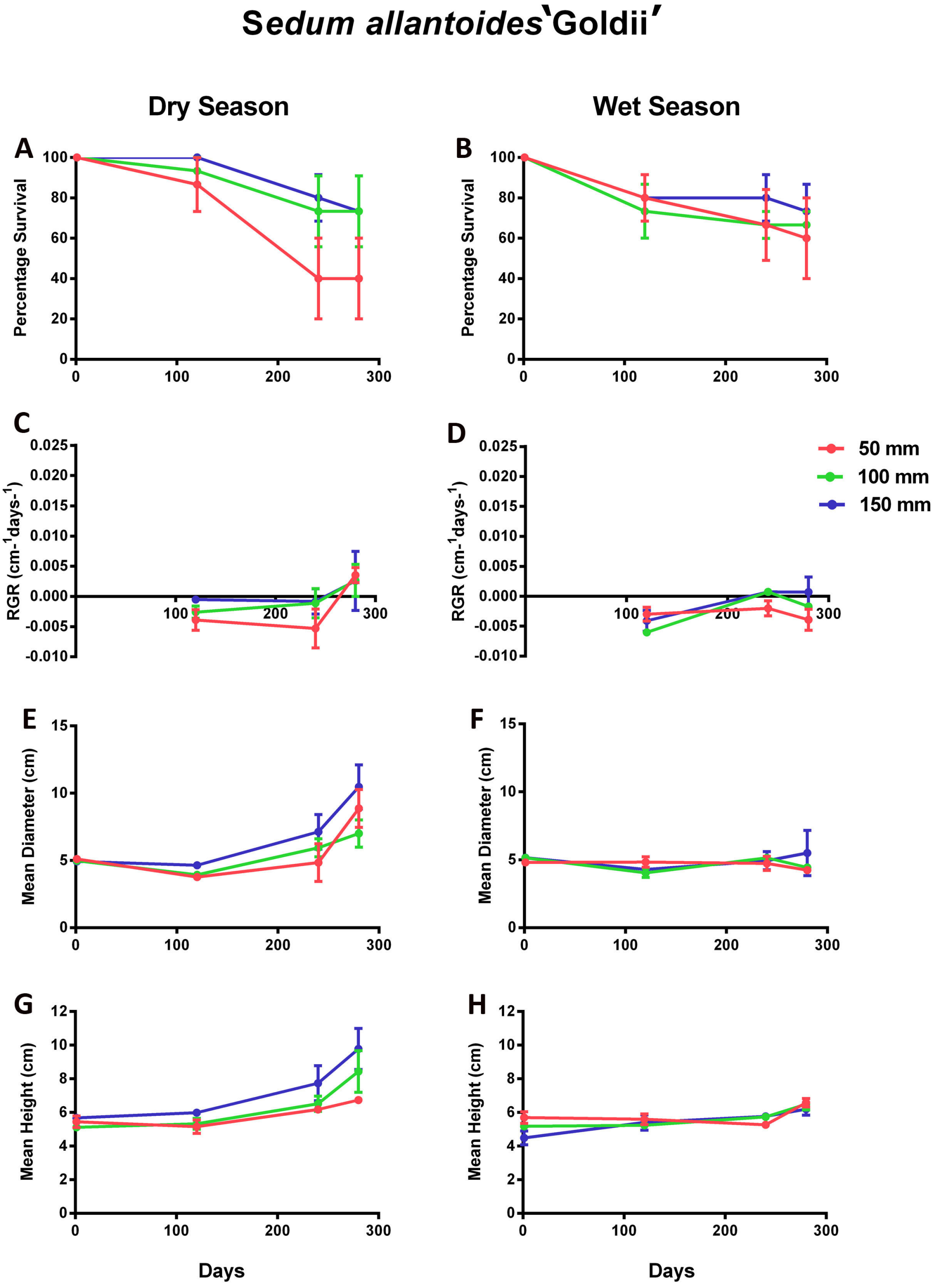


Figure 3.2.2 ***Sedum allantoides*** **'Goldii', Survival percentage Dry Season (A), Survival percentage Wet Season (B), Mean Diameter RGR ±SEM Dry Season (C), Mean Diameter RGR ±SEM Wet Season (D), Mean Diameter ±SEM Dry Season (E), Mean Diameter ±SEM Wet Season (F), Mean Height ± SEM Dry Season (G), Mean Height ±SEM Wet Season (H) during 280 days at two planting seasons and three depths. Negative RGR is due to shrinking of the species during drought or due to diseases.**

3.2.2.2 Sedum allantoides

Sedum allantoides had significantly higher survival when planted during the wet season ($p<0.05$, Tukey HSD), and no significant differences were found between depths, neither within nor between seasons ($p>0.05$, Tukey HSD) (Figure 3.2.3 A and B). Despite improved wet season established plant survival, this species had a significantly higher diameter RGR, when planted during the dry season ($p<0.05$, Tukey HSD) (Figure 3.2.3 C and D), although in contrast, it had a significantly higher mean diameter when planted during the wet season ($p<0.05$, Tukey HSD) (Figure 3.2.3 E and F). This may be due to belowground processes, such as enhanced root mass, which may have been achieved earlier if planted in the wet season.

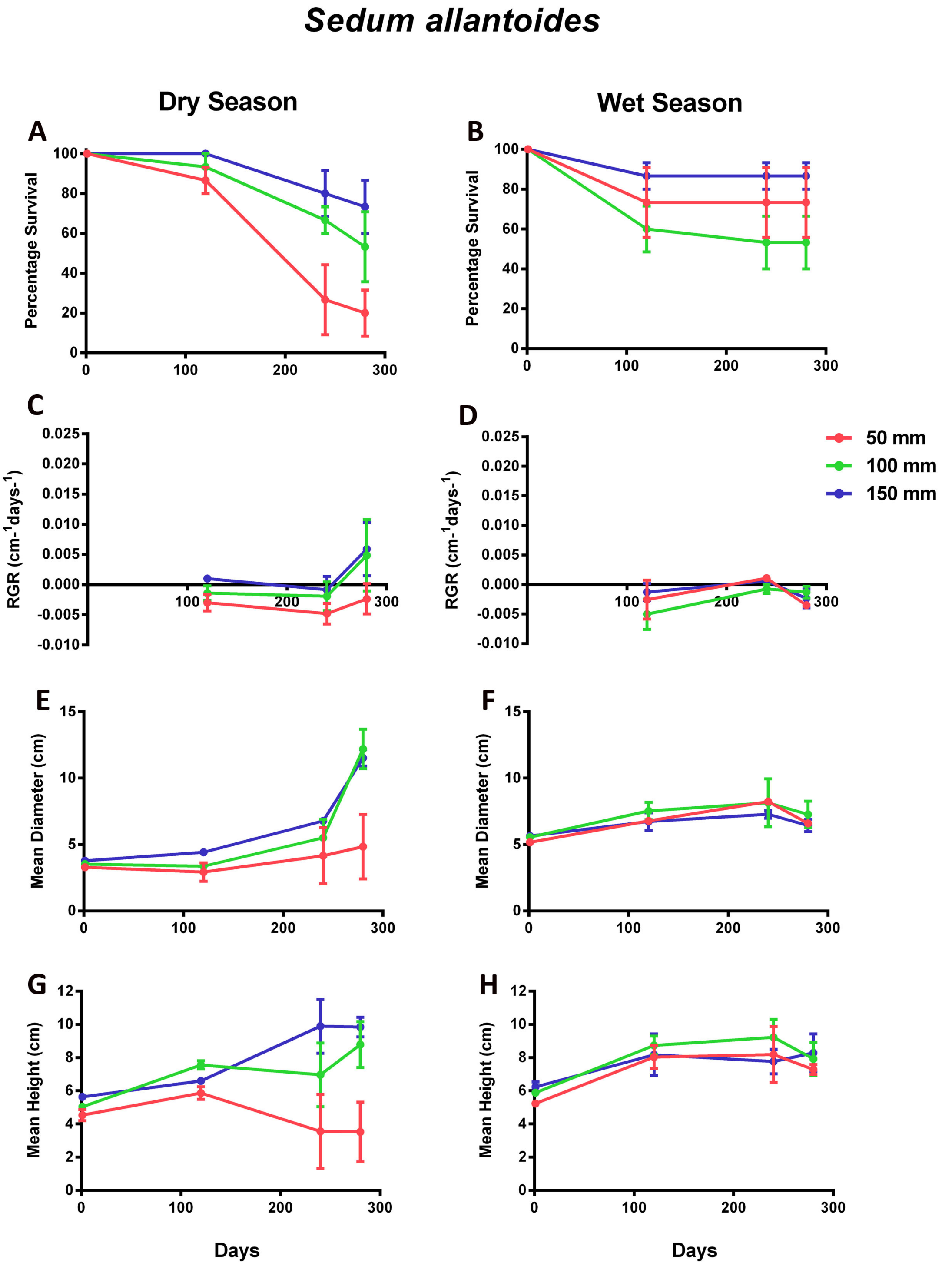


Figure 3.2.3 ***Sedum allantoides*****, Survival percentage Dry Season (A), Survival percentage Wet Season (B), Mean Diameter RGR ±SEM Dry Season (C), Mean Diameter RGR ±SEM Wet Season (D), Mean Diameter ±SEM Dry Season (E), Mean Diameter ±SEM Wet Season (F), Mean Height ± SEM Dry Season (G), Mean Height ±SEM Wet Season (H) during 280 days at two planting seasons and three depths. Negative RGR is due to shrinking of the species during drought or due to diseases.**

3.2.2.3 Sedum confusum

Sedum confusum was one of the most obvious responsive species to the treatments. Survival was significantly higher for *S. confusum* when established during the wet season ($p<0.005$, Tukey HSD) (Figure 3.2.4 A and B). Diameter RGR was also significantly higher for the wet season established plants ($p<0.05$, Tukey HSD) (Figure 3.2.4 C and D), but no differences were found between depths ($p>0.05$, Tukey HSD). Both, mean diameter and mean height of *S. confusum* were significantly greater for plantings during the wet season ($p<0.05$, Tukey HSD) (Figure 3.2.4 E and F). Furthermore, this species was sensitive to shallow substrates: *S. confusum* had significantly greater diameters at the 100 and 150 mm depths than at the 50 mm depth ($p<0.01$, Tukey HSD) (Figure 3.2.4 E and F). The depth factor also significantly affected height, with *S. confusum* growing significantly taller when grown in 150 and 100 mm depths ($p<0.05$, Tukey HSD) compared to 50 mm depth (Figure 3.2.4 G and H).

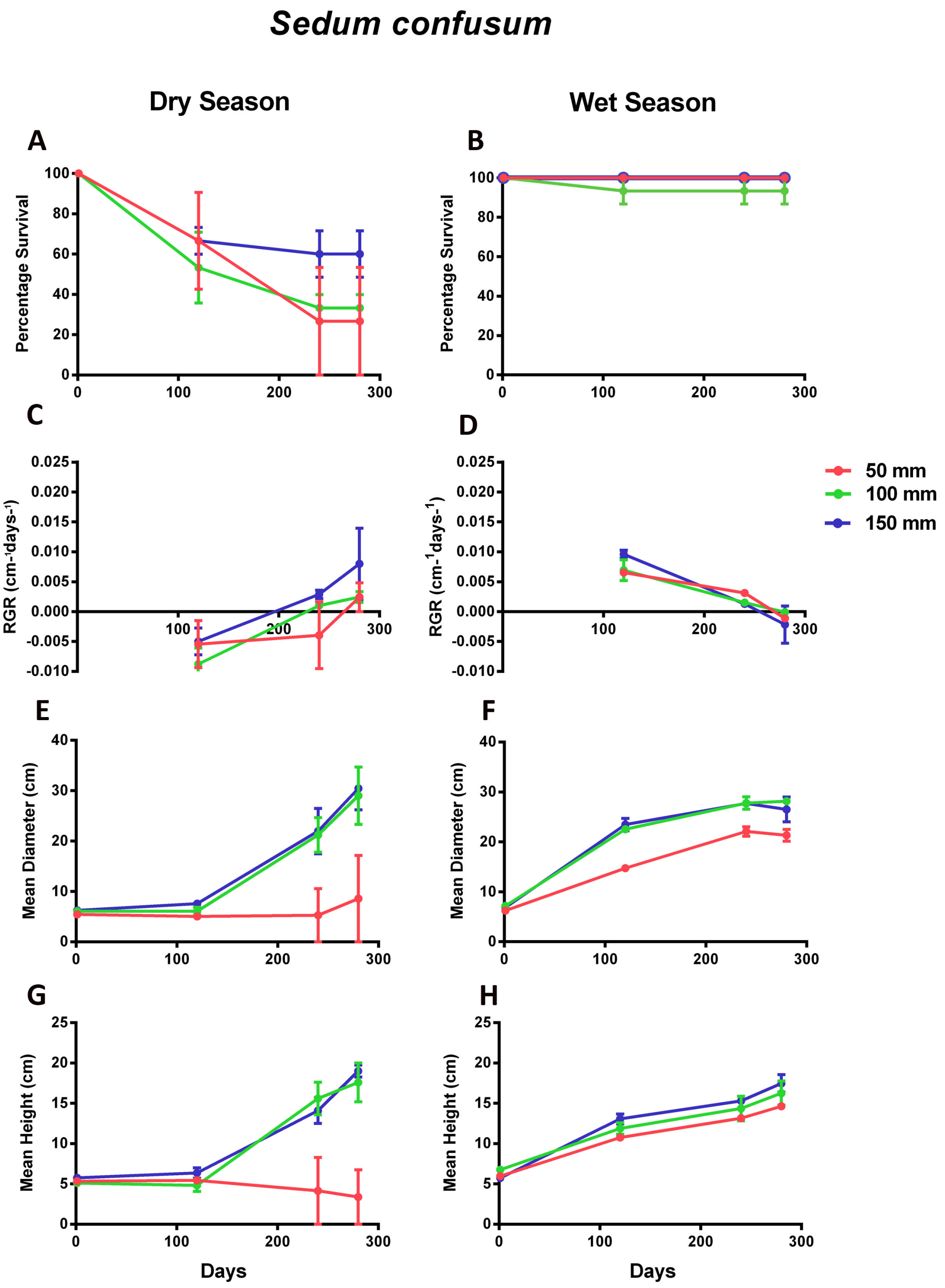


Figure 3.2.4 ***Sedum confusum*, Survival percentage Dry Season (A), Survival percentage Wet Season (B), Mean Diameter RGR ±SEM Dry Season (C), Mean Diameter RGR ±SEM Wet Season (D), Mean Diameter ±SEM Dry Season (E), Mean Diameter ±SEM Wet Season (F), Mean Height ±SEM Dry Season (G), Mean Height ±SEM Wet Season (H) during 280 days at two planting seasons and three depths. Negative RGR is due to shrinking of the species during drought or due to diseases.**

3.2.2.4 Sedum griseum

Sedum griseum is one of the few species that was not significantly affected in survival by planting season ($p > 0.05$, Tukey HSD). *S. griseum* had very high survival rates in both seasons. However, the dry season-established plants had a drop in survival in the 50 mm depth, but this mortality actually recovered due to the serendipitous rooting of some fallen shoots when water was available (Figure 3.2.5 A and B), testimony of the success of the Crassulaceae survival mechanism. This species had a significantly higher RGR when established during the dry season compared to the wet season ($p=0.005$, Tukey HSD) (Figure 3.2.5 C and D). The mean diameter of *S. griseum* was also highly significantly greater when established during the dry season ($p=0.009$, Tukey HSD) (Figure 3.2.5 E and F). For the two seasons, the mean diameter of *S. griseum* was significantly higher at the 100 and 150 mm depth than at 50 mm depth ($p<0.05$, Tukey HSD) (Figure 3.2.5 E and F). In contrast, *S. griseum* grew significantly taller when established during the dry season ($p<0.05$, Tukey HSD), perhaps due to the competition with other tall plants such as *S. confusum*. During the dry season *S. griseum* grew significantly taller when grown in 150 mm depth than in 50 mm depth ($p=0.018$, Tukey HSD), (Figure 3.2.5 G and H).

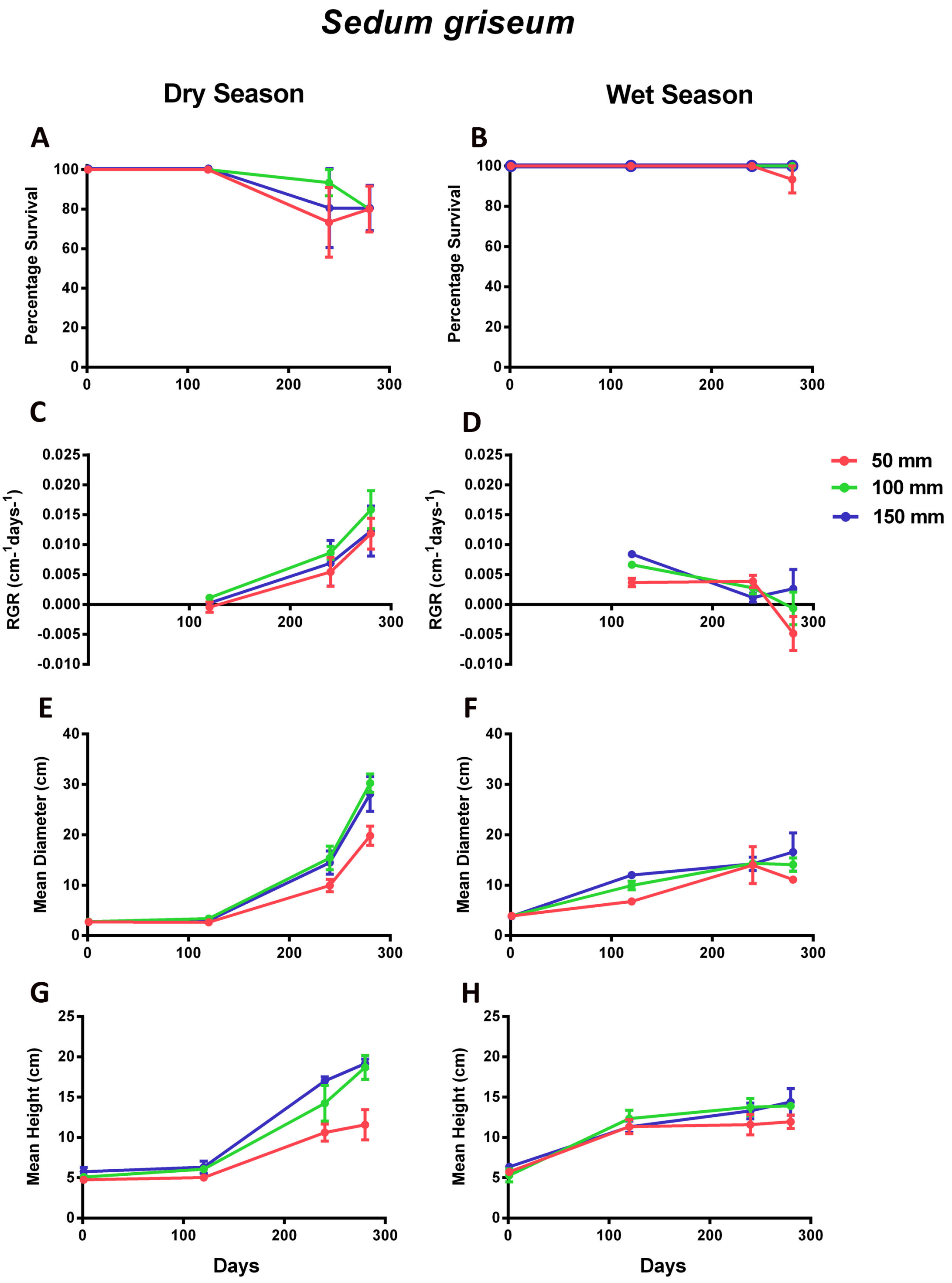


Figure 3.2.5 ***Sedum griseum*****, Survival percentage Dry Season (A), Survival percentage Wet Season (B), Mean Diameter RGR ±SEM Dry Season (C), Mean Diameter RGR ±SEM Wet Season (D), Mean Diameter ±SEM Dry Season (E), Mean Diameter ±SEM Wet Season (F), Mean Height ±SEM Dry Season (G), Mean Height ±SEM Wet Season (H) during 280 days at two planting seasons and three depths. Negative RGR is due to shrinking of the species during drought or due to diseases.**

3.2.2.5 Sedum jurgensenii **ssp.** ***jurgensenii***

Sedum jurgensenii had a significantly higher survival when established during the wet season ($p<0.05$, Tukey HSD) (Figure 3.2.6 A and B), but no significant differences were found between depths within or between seasons ($p>0.05$, Tukey HSD). The diameter relative growth rate was significantly higher for plants established during the wet season ($p<0.05$, Tukey HSD) (Figure 3.2.6 C and D), but no differences were found in diameter between seasons and depths ($p>0.05$, Tukey HSD) (Figure 3.2.6 E and F). In contrast, *S. jurgensenii* grew significantly taller when established during the wet season ($p<0.05$, Tukey HSD) (Figure 3.2.6 G and H).

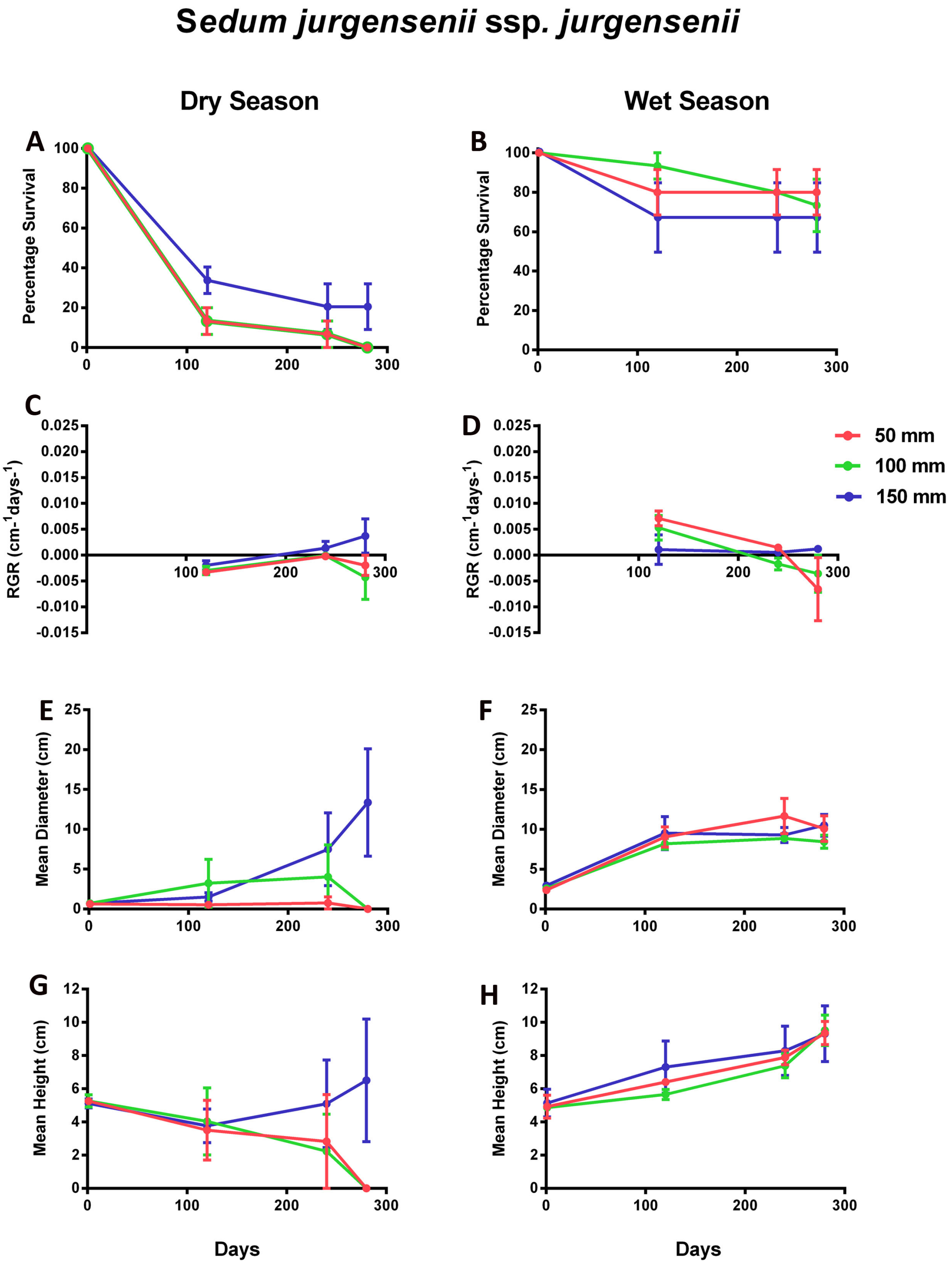


Figure 3.2.6 ***Sedum jurgensenii*** **ssp.** ***jurgensenii*****, Survival percentage Dry Season (A), Survival percentage Wet Season (B), Mean Diameter RGR ±SEM Dry Season (C), Mean Diameter RGR ±SEM Wet Season (D), Mean Diameter ±SEM Dry Season (E), Mean Diameter ±SEM Wet Season (F), Mean Height ±SEM Dry Season (G), Mean Height ±SEM Wet Season (H) during 280 days at two planting seasons and three depths. Negative RGR is due to shrinking of the species during drought or due to diseases.**

3.2.2.6 ***Sedum* x *luteoviride***

Sedum x *luteoviride*, like *Sedum griseum*, did not show significant differences in survival between planting seasons, nor significant differences between depths ($p>0.05$, Tukey HSD) (Figure 3.2.7 A and B). The diameter relative growth rate of *S.* x *luteoviride* was, however, significantly higher in plants grown during the dry season ($p<0.005$, Tukey HSD) (Figure 3.2.7 C and D), while the mean diameter achieved was significantly greater for the plants grown in the wet season ($p<0.05$, Tukey HSD) (Figure 3.2.7 E and F).

Sedum x *luteoviride*

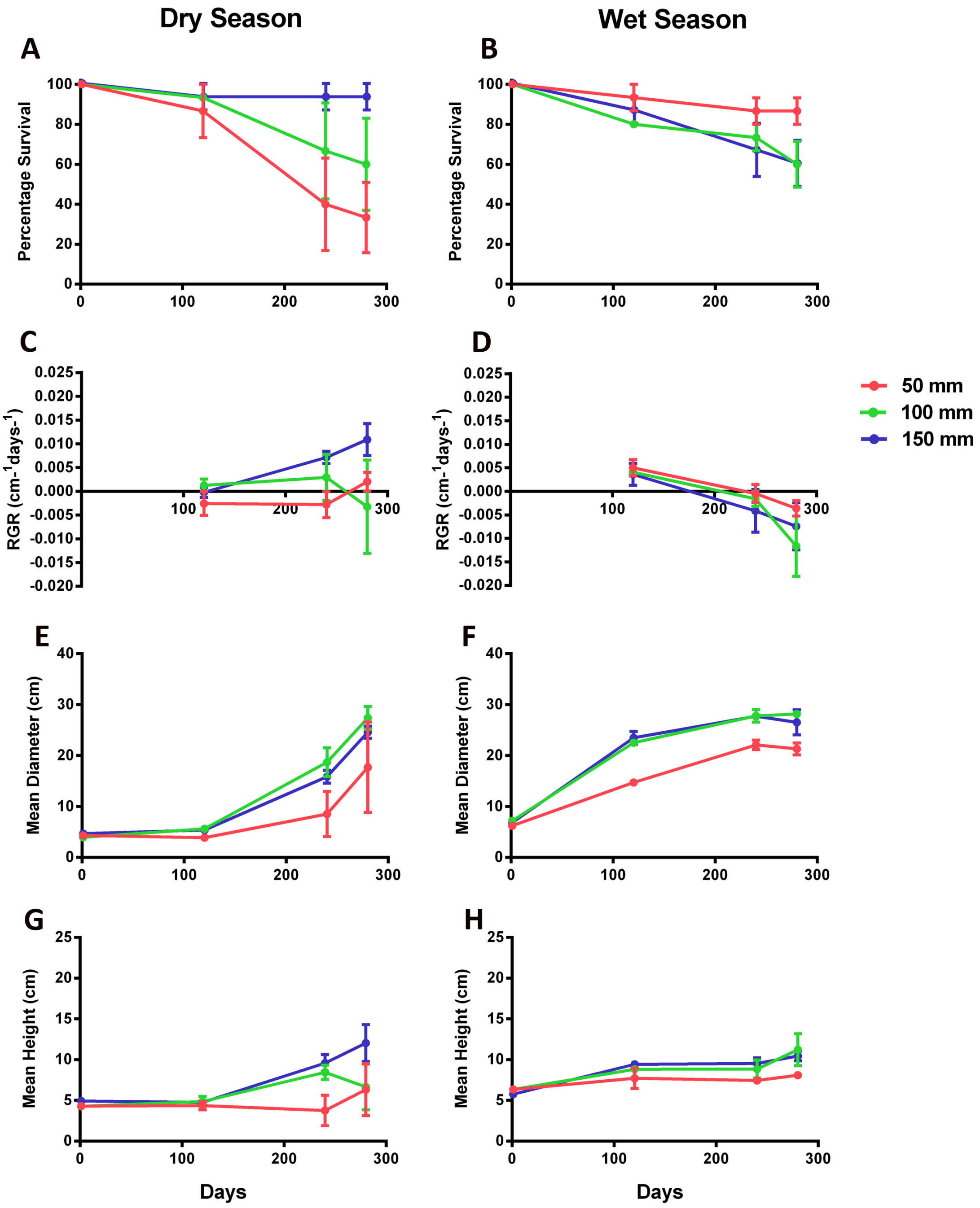


Figure 3.2.7 ***Sedum*** **x** ***luteoviride*****, Survival percentage Dry Season (A), Survival percentage Wet Season (B), Mean Diameter RGR ±SEM Dry Season (C), Mean Diameter RGR ±SEM Wet Season (D), Mean Diameter ±SEM Dry Season (E), Mean Diameter ±SEM Wet Season (F), Mean Height ±SEM Dry Season (G), Mean Height ±SEM Wet Season (H) during 280 days at two planting seasons and three depths. Negative RGR is due to shrinking of the species during drought or due to diseases.**

3.2.2.7 Sedum mexicanum

Sedum mexicanum achieved significantly higher survival rates if established during the wet season ($p<0.05$, Tukey HSD) (Figure 3.2.8 A and B). The diameter relative growth rate, however, was significantly higher when planted during the dry season ($p<0.05$, Tukey HSD) (Figure 3.2.8 C and D). Unfortunately, *S. mexicanum* did very poorly across all treatments. The provenance of this species remains unknown and, judging by the species responses to season and depths in this experiment, it might well be native to shaded and rainy areas of Mexico since it does not withstand droughts.

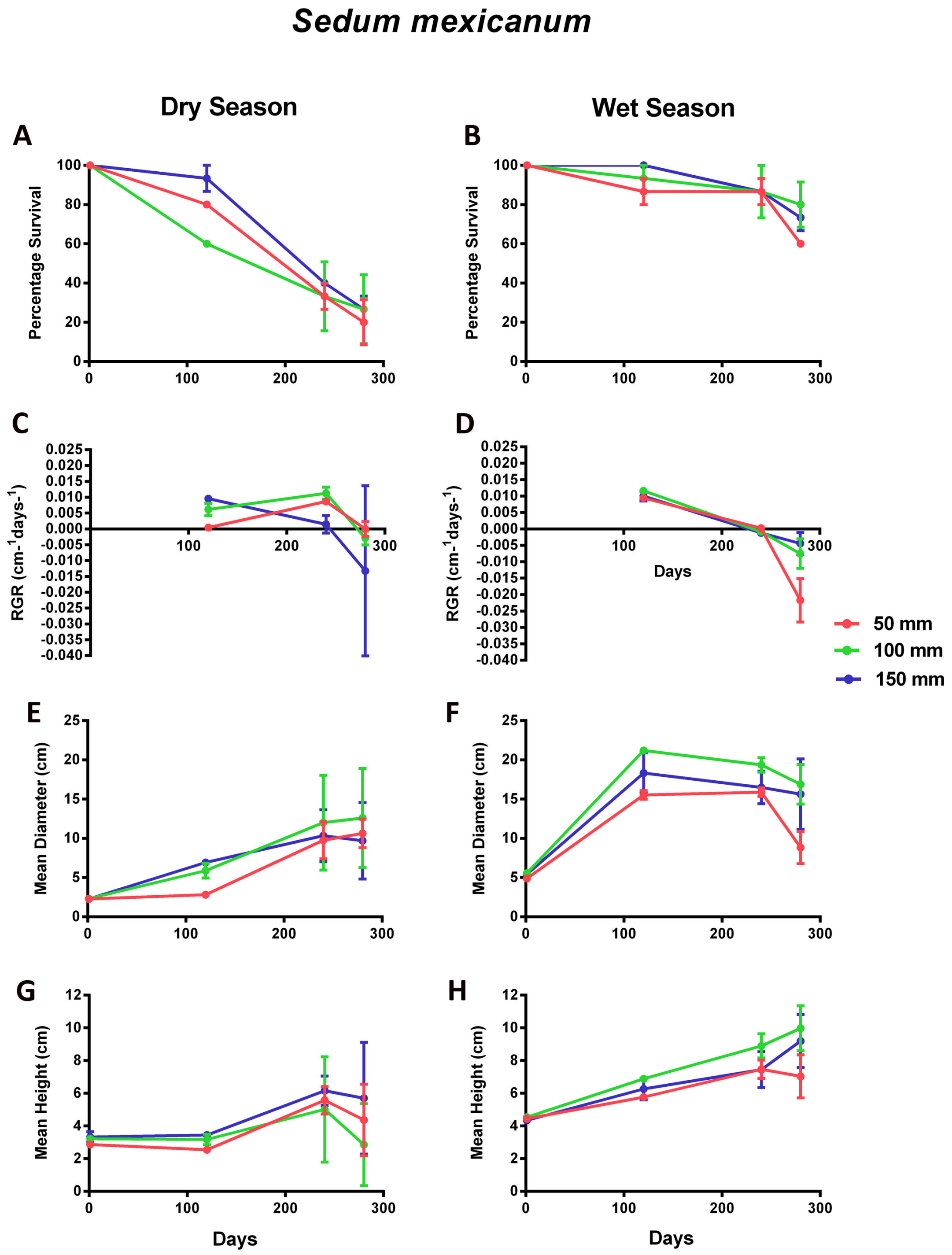


Figure 3.2.8 ***Sedum mexicanum*****, Survival percentage Dry Season (A), Survival percentage Wet Season (B), Mean Diameter RGR ±SEM Dry Season (C), Mean Diameter RGR ±SEM Wet Season (D), Mean Diameter ±SEM Dry Season (E), Mean Diameter ±SEM Wet Season (F), Mean Height ±SEM Dry Season (G), Mean Height ±SEM Wet Season (H) during 280 days at two planting seasons and three depths. Negative RGR is due to shrinking of the species during drought or due to diseases.**

3.2.2.8 Sedum oxypetalum

Sedum oxypetalum had a significantly higher survival rate ($p<0.05$, Tukey HSD) (Figure 3.2.9 A and B), diameter relative growth rate, and mean diameter ($p<0.05$, Tukey HSD) for plants established during the wet season (Figure 3.2.9 C and D, E and F). Wet season established plants also grew significantly taller than dry season-established individuals ($p<0.005$, Tukey HSD) (Figure 3.2.9 G and H). This species in its native habitat grows on top of lava rocks with very little soil, and therefore, it seems that the only requirement for it to establish is to be planted during the summer months when there is enough water to develop an extensive root system.

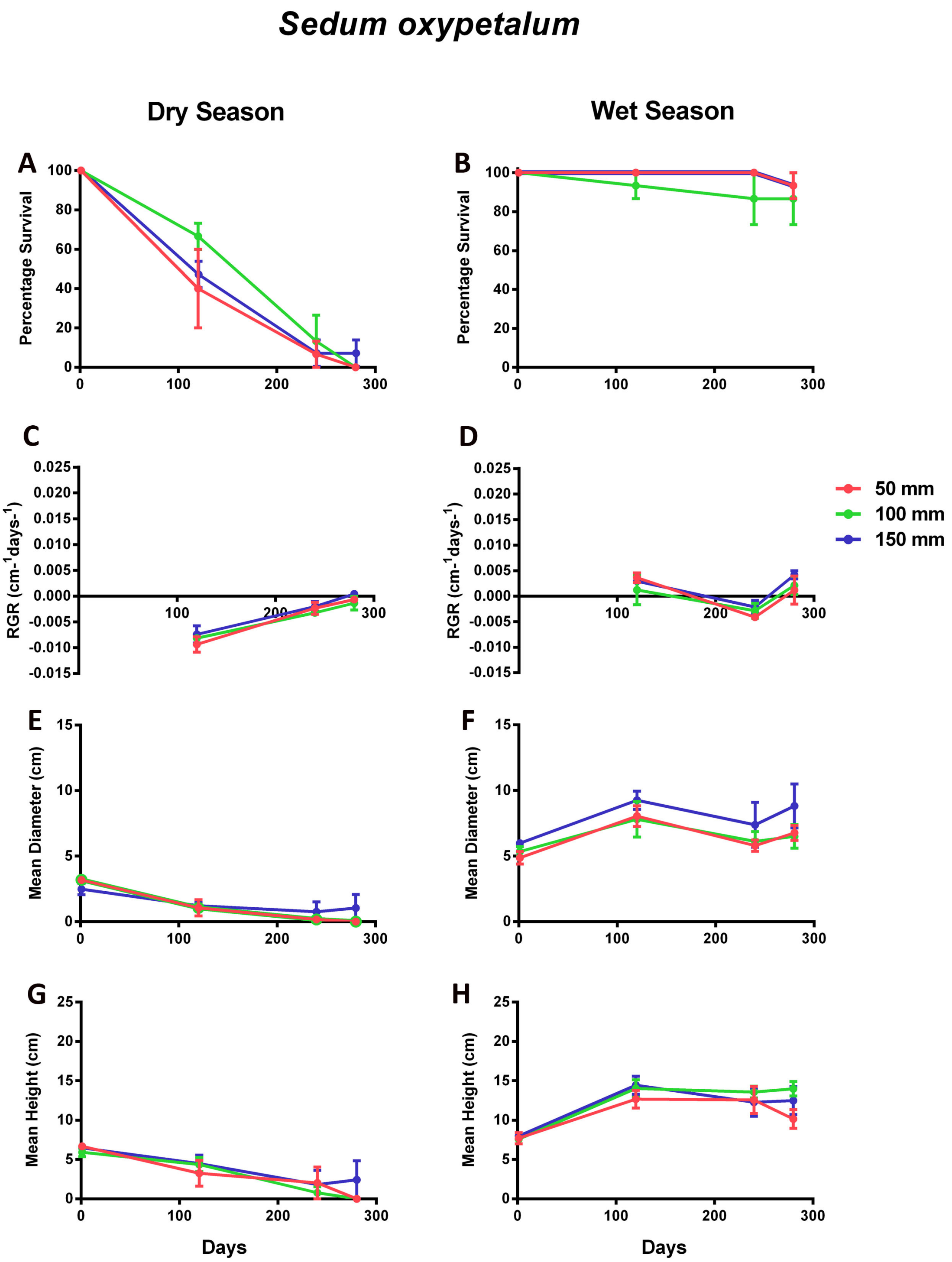


Figure 3.2.9 ***Sedum oxypetalum*****, Survival percentage Dry Season (A), Survival percentage Wet Season (B), Mean Diameter RGR ±SEM Dry Season (C), Mean Diameter RGR ±SEM Wet Season (D), Mean Diameter ±SEM Dry Season (E), Mean Diameter ±SEM Wet Season (F), Mean Height ±SEM Dry Season (G), Mean Height ±SEM Wet Season (H) during 280 days at two planting seasons and three depths. Negative RGR is due to shrinking of the species during drought or due to diseases.**

3.2.2.9 Sedum x *rubrotinctum*

Sedum x *rubrotinctum's* survival was significantly higher when established during the wet season (p<0.05, Tukey HSD) (Figure 3.2.10 A and B). The diameter relative growth rate, however, was significantly higher in *S.* x *rubrotinctum* when planted during the dry season (p<0.05, Tukey HSD) (Figure 3.2.10 C and D), although the mean diameter achieved was significantly greater (p<0.005, Tukey HSD) (Figure 3.2.10 E and F), and mean height achieved where significantly taller when planted in the wet season (p<0.05, Tukey HSD) (Figure 3.2.10 G and H). Plants grown in 100 mm depth were significantly taller than those in the 50 mm depth overall (p<0.05, Tukey, HSD). However, for wet season establishment, plants in the 50 mm depth were significantly higher than the 100 mm and 150 mm depths (p<0.05, Tukey HSD), while in the dry season the 100 mm depth was significantly higher than the 50 mm depth (p<0.05, Tukey HSD) (Figure 3.2.10 G and H). This could be explained by availability of open spaces' found across the substrate at the 50 mm depth, in contrast to the big canopies achieved by *S. confusum* and *S. griseum* which arguably constrained shorter species in the 100 and 150 mm depths.

Sedum x *rubrotinctum*

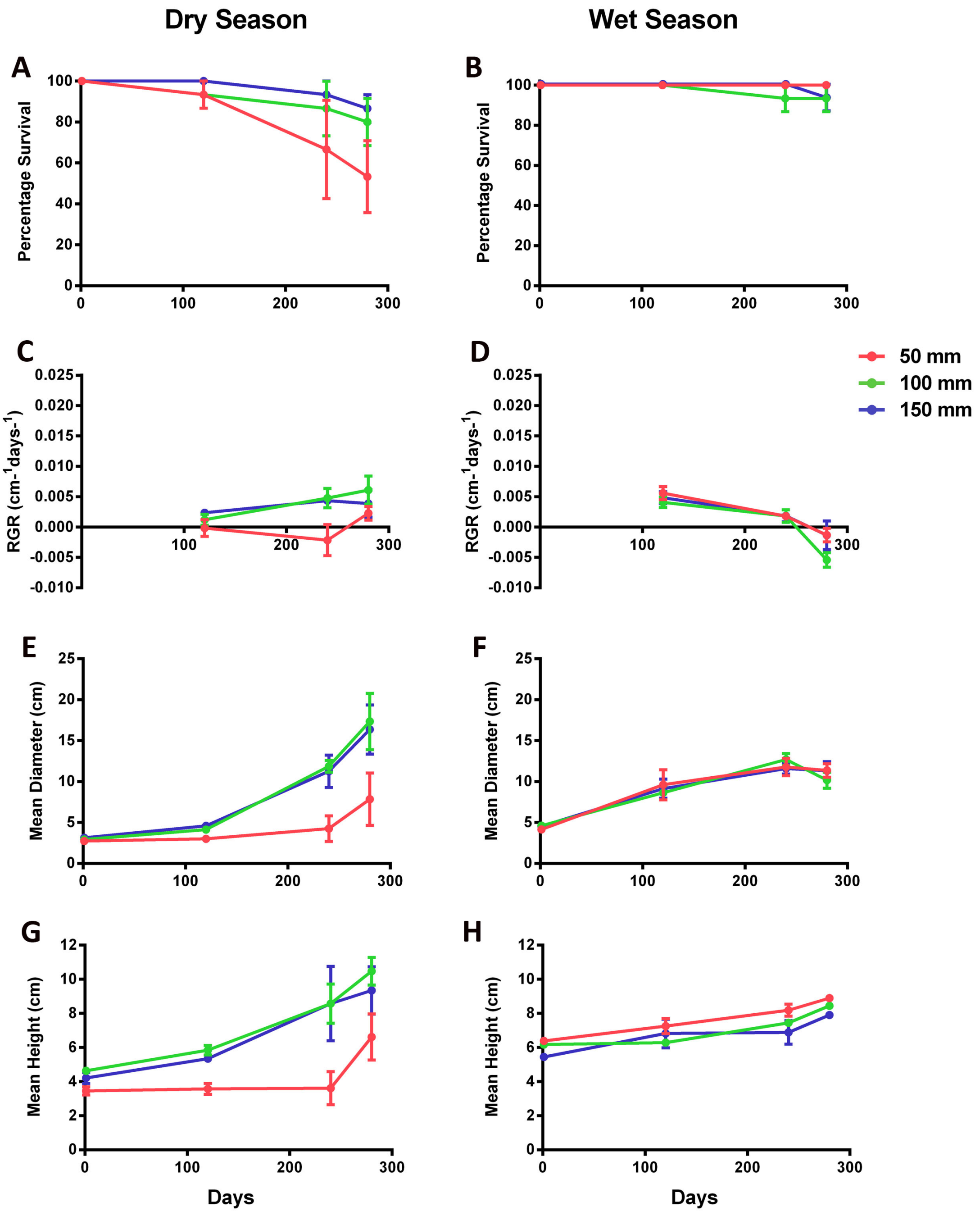


Figure 3.2.10 ***Sedum* x *rubrotinctum*, Survival percentage Dry Season (A), Survival percentage Wet Season (B), Mean Diameter RGR ±SEM Dry Season (C), Mean Diameter RGR ±SEM Wet Season (D), Mean Diameter ±SEM Dry Season (E), Mean Diameter ±SEM Wet Season (F), Mean Height ±SEM Dry Season (G), Mean Height ±SEM Wet Season (H) during 280 days at two planting seasons and three depths. Negative RGR is due to shrinking of the species during drought or due to diseases.**

3.2.2.10 Sedum stahlii

Sedum stahlii survival was significantly higher for those individuals planted during the wet season ($p<0.05$, Tukey HSD) (Figure 3.2.11 A and B). The diameter relative growth rate of *S. stahlii* was significantly higher for the dry season established plants ($p<0.05$, Tukey HSD) (Figure 3.2.11 C and D). The mean diameter was significantly higher for plants established during the wet season ($p=0.007$, Tukey HSD) (Figure 3.2.11 E and F). Depth significantly affected diameter ($p<0.05$); the diameter achieved by those grown in 150 mm substrate was significantly higher than the diameter of plants in the 50 mm depth ($p=0.024$, Tukey HSD) (Figure 3.2.11 E and F).

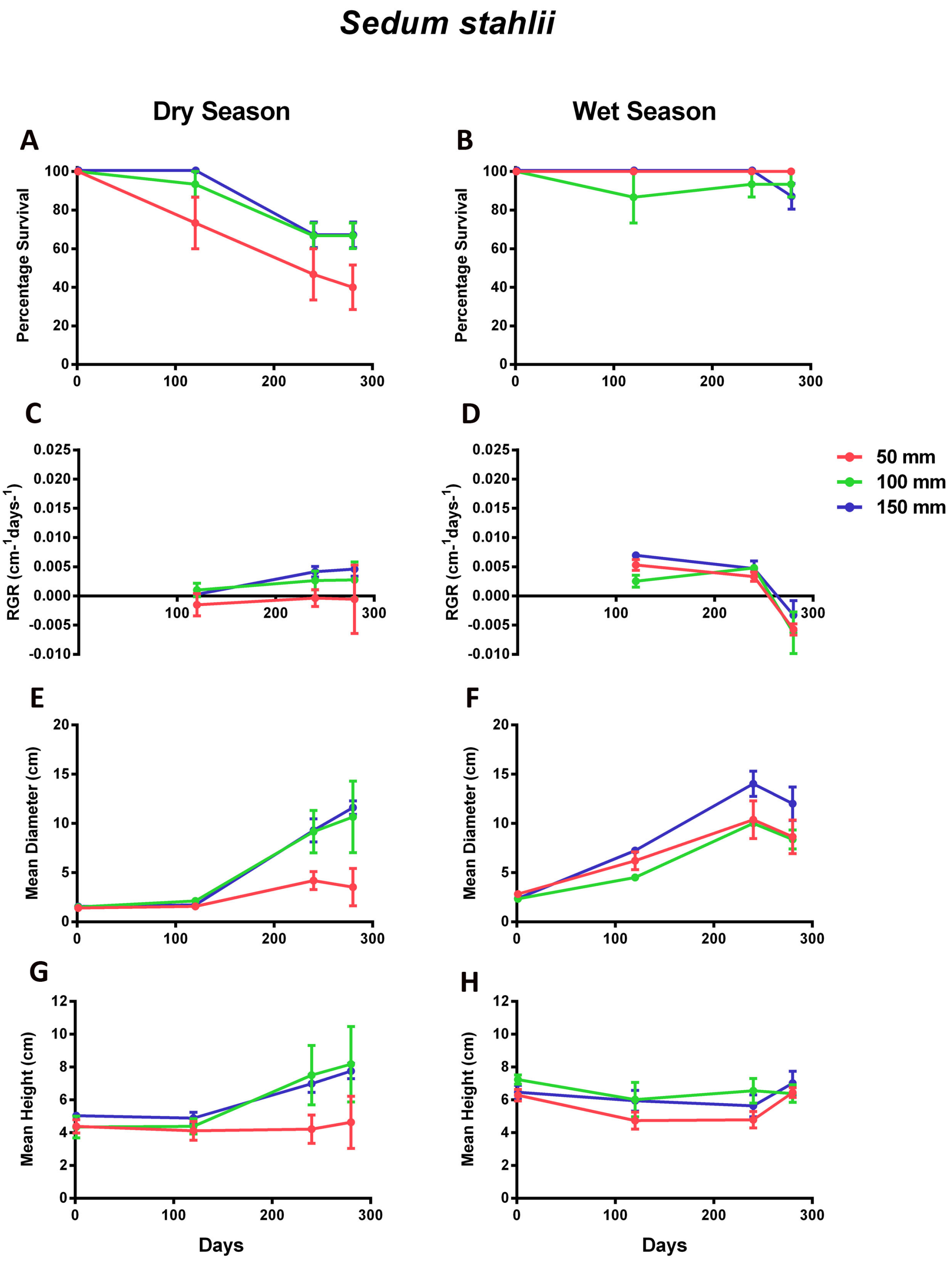


Figure 3.2.11 ***Sedum stahlii*****, Survival percentage Dry Season (A), Survival percentage Wet Season (B), Mean Diameter RGR ±SEM Dry Season (C), Mean Diameter RGR ±SEM Wet Season (D), Mean Diameter ±SEM Dry Season (E), Mean Diameter ±SEM Wet Season (F), Mean Height ±SEM Dry Season (G), Mean Height ±SEM Wet Season (H) during 280 days at two planting seasons and three depths. Negative RGR is due to shrinking of the species during drought or due to diseases.**

3.2.3 Season and depth results for pool species

3.2.3.1 Survival

For the overall model, the differences in survival were highly significant (p<0.001, Greenhouser-Geisser correction). Season significantly affected survival (p<0.001, Greenhouser-Geisser correction), with a higher survival rate across plant species and individuals for those planted during the wet season (Figure 3.2.12). Survival between the dry and wet season planting treatments is still significantly different at day 280, suggesting that even though water became available during the last days of the dry planting season, some plants were still unable to fully recover from the growth inhibition caused by the initial deficit during establishment.

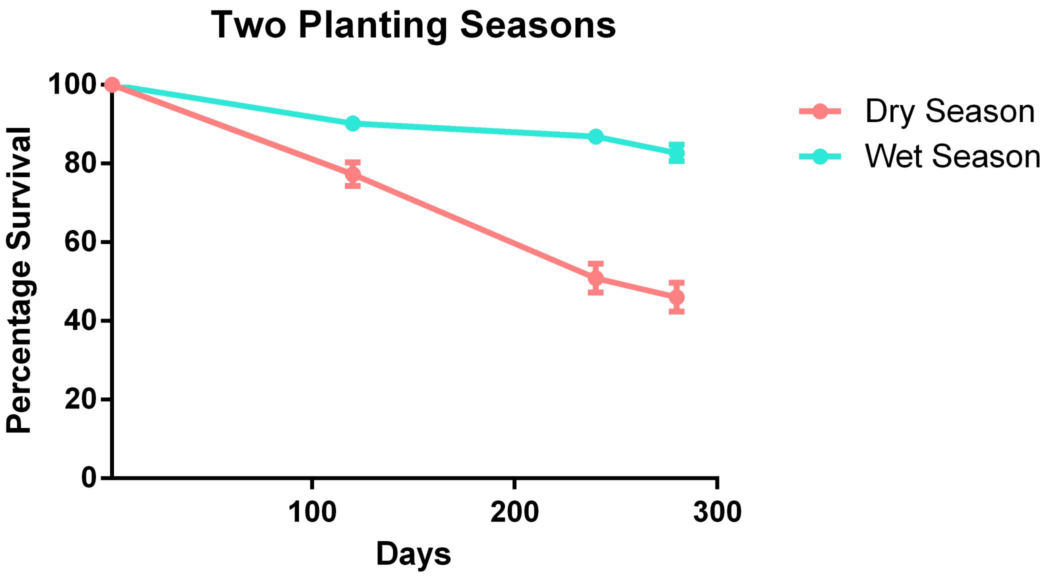


Figure 3.2.12 Repeated measures of survival percentage for all species and depths at two seasons. ±SEM bars for between subjects.

Depth highly significantly affected survival (p<0.005, Greenhouser-Geisser correction), with improved rates of survival at 150 mm than at 50 mm depth (p<0.05, Tukey, HSD) (Figure 3.2.13). Despite this, survival between depths 100 and 150 mm and 100 and 50 mm did not significantly differ in this analysis (Figure 3.2.13).

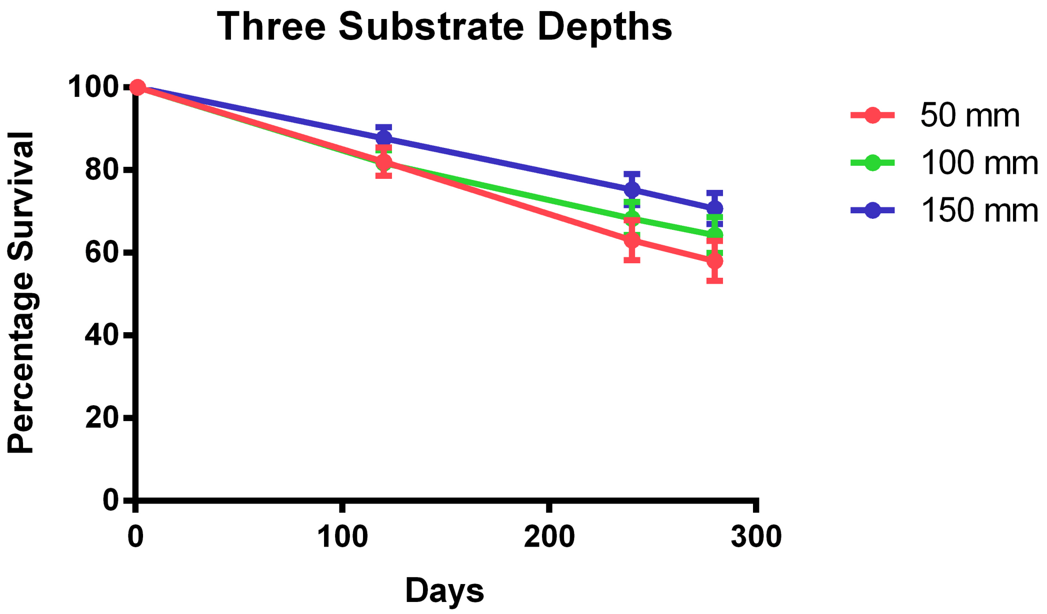


Figure 3.2.13 Repeated measures of percentage of survival of all species and all seasons at three depths. ±SEM bars only for between subjects.

The survival for both season and depths shows that, for plants established during the dry season, both 150 and 100 mm depths resulted in significantly lower mortality than the 50 mm depth ($p<0.05$, Tukey HSD). In contrast for plants established in the wet season, there were no significant differences in survival between the three depths ($p>0.05$, Tukey HSD) (Figure 3.2.14). The increased mortality observed for individuals planted during the dry season intensifies as time passes, even when water becomes available (Figure 3.2.14). The fact that this trend is not corrected, even in the 150 mm depth, indicates that in climates Cwb (warm temperate with dry winter and warm summer) it is highly recommended to plant with un-rooted cuttings only at the end of spring or at the beginning of summer, when timely rains will guarantee greater survival of the green roof. It is necessary to underline once more that this experiment did not consider the use of plug plants, which might have a greater chance of successful establishment and survival if planted with supplemental water during the drought. However, their greater cost and more labour-intensive installation can be prohibitive or undesirable in Mexico.

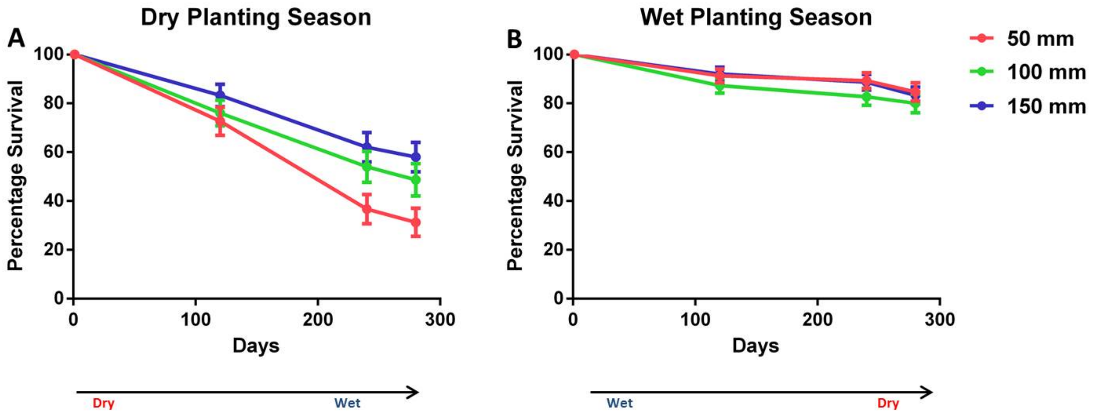


Figure 3.2.14 Repeated measures of percentage survival for Dry planting season ±SEM (A) and Wet planting season ±SEM (B) at three depths for all species. ±SEM bars only for between subjects.

For overall survival, there were no significant differences between depths within seasons, or depths between seasons. Nevertheless, there were significant differences in survival for most of the species between seasons. *Sedum allantoides*, *S. confusum, S. jurgensenii*, *S. mexicanum*, *S. oxypetalum, S. stahlii* and *S.* x *rubrotinctum* had a significantly higher survival if planted in the wet season (Figure 3.2.15). *S. griseum* and *S.* x *luteoviride* did not have significant differences between seasons but, *S. griseum* had the highest survival of all species in both seasons (Figure 3.2.15). The high survival percentage of *S. griseum* could be attributed to the naturally highly porous substrates and exposure conditions of the sites where this species is found in the wild (Clausen, 1959).

The survival data for the two seasons strongly suggests that the majority of the species studied are highly sensitive to water availability at the beginning of their planting and establishment. This is particularly evident in the species *Sedum allantoides* Goldii, *S. jurgensenii*, *S. oxypetalum, S. mexicanum, S. confusum* and *S. stahlii* (Figure 3.2.15). In contrast, species like *S. griseum*, *S.* x *luteoviride* and even *S.* x *rubrotinctum,* which had a significantly lower survival were planted during the dry season, appear to be ideal for cases where low water availability during the establishment period is unavoidable. Other situations in which these species may be very helpful include difficult zones like the edges of the roofs.

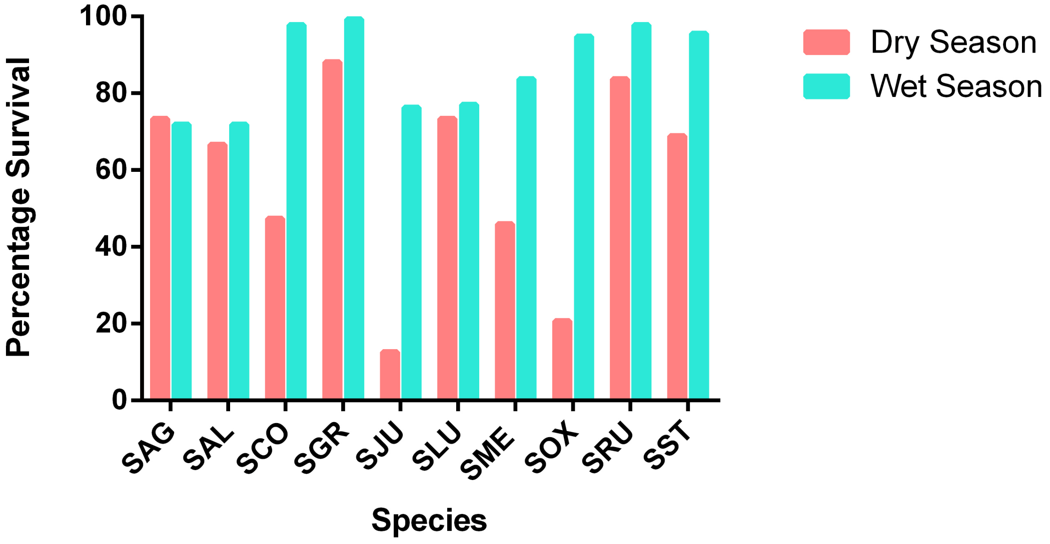


Figure 3.2.15 Final percentage Survival at two planting seasons for SAG *S. allantoides* Goldii, SAL *S. allantoides,* SCO *S. confusum,* SGR *S. griseum,* SJU *S. jurgensenii,* SLU *S.* x *luteoviride,* SME *S. mexicanum,* SOX *S. oxypetalum,* SRU *S.* x *rubrotinctum* and SST *S. stahlii.* ±SEM bars only for between subjects.

3.2.3.2 Diameter Relative Growth Rate

Planting season significantly affected the diameter RGR (p=0.005, Greenhouse-Geisser correction) (Figure 3.2.16), with higher diameter RGR in plants planted during the dry season. In contrast, depth did not have any significant effect (p=0.259, Greenhouse-Geisser correction) (Figure 3.2.17).

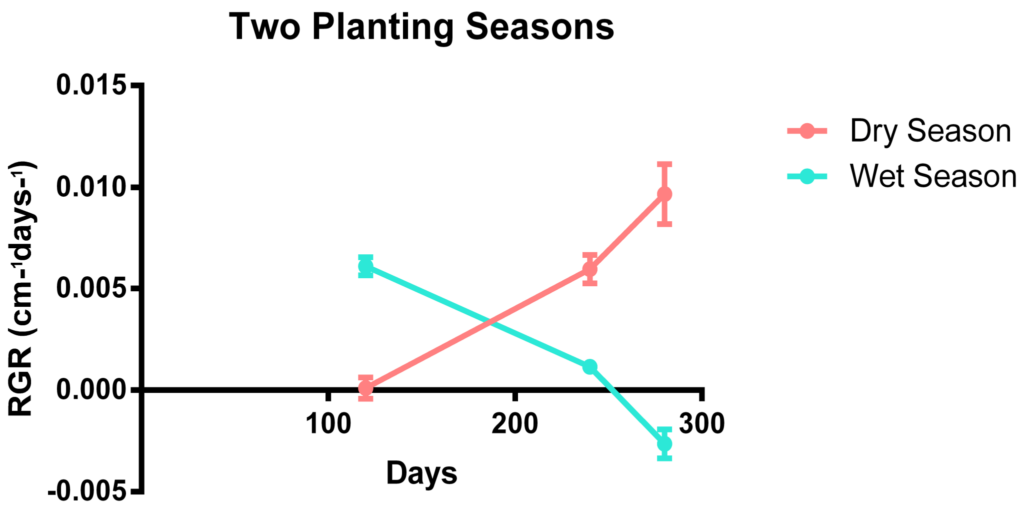


Figure 3.2.16 RGR of diameters from pool data in two planting seasons. ±SEM bars only for between subjects. Negative RGR is due to shrinking of the species during drought or due to diseases.

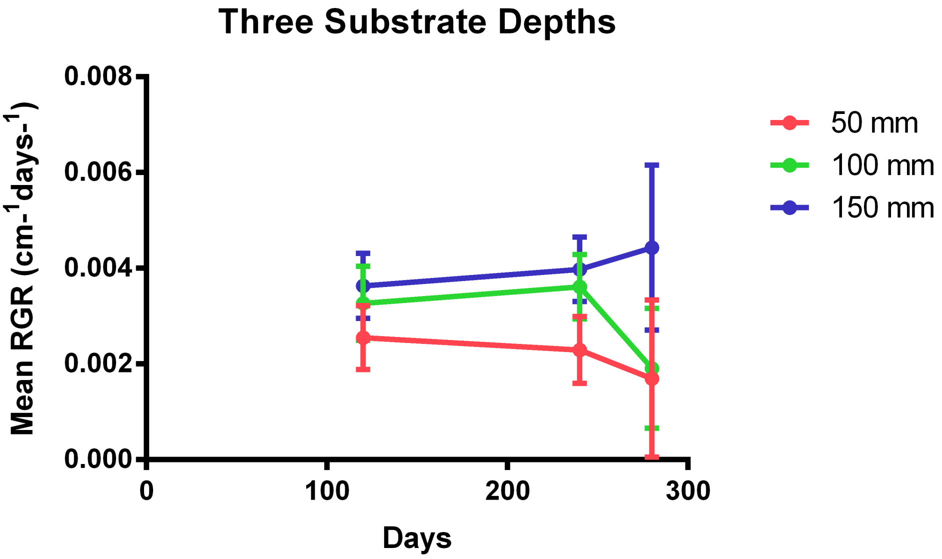


Figure 3.2.17 Repeated measures of RGR of all species and all seasons at three substrate depths. ±SEM bars only for between subjects. Negative RGR is due to shrinking of the species during drought.

For the dry season planting, only the mean RGR of the 150 mm depth was significantly higher than that of the 50 mm depth (p=0.001, Tukey HSD) (Figure 3.2.18). For the wet planting season, there were no significant differences between depths (p>0.05, Tukey HSD) (Figure 3.2.18).

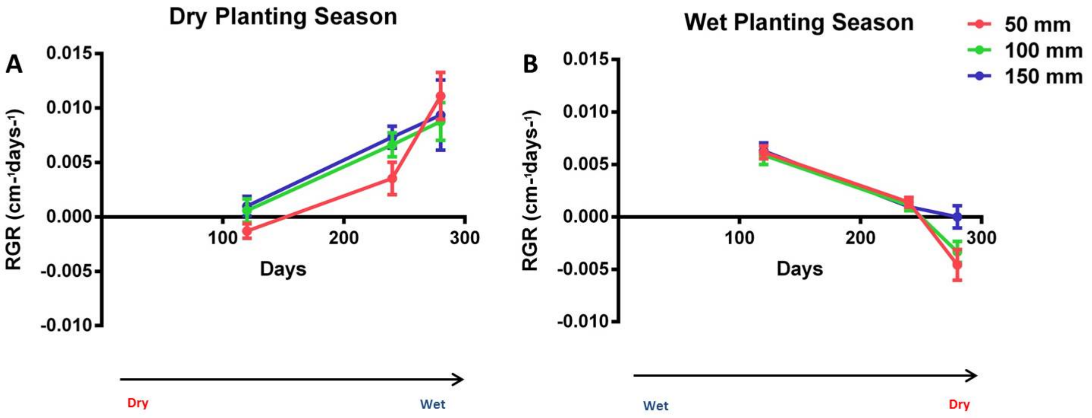


Figure 3.2.18 Repeated measures of mean diameter relative growth rate for Dry planting season ±SEM (A) and Wet planting season ±SEM (B) at three depths for all species. ±SEM bars only for between subjects. Negative RGR is due to shrinking of the species during drought or due to diseases.

At all three depths, the RGR for each species increases over time for plants established in the dry season, but decreases for the plants established in the wet season (Figure 3.2.18). This trend is almost definitely related to the change of water availability over the duration of the experiment, in combination with the accompanying change in intensity of solar radiation as cloud cover shifts. This can be seen on both planting seasons at day 120 when patterns of precipitation changed.

Differences in diameter RGR between species by season

During the dry season the mean diameter RGR for all days and all depths showed that *S. griseum* had significantly higher mean RGR than *S. allantoides* Goldii, *S. allantoides*, *S. confusum*, *S. jurgensenii*, and *S. mexicanum*, *S. oxypetalum* and *S. stahlii* (all $p<0.05$, Tukey HSD) (Figure 3.2.19). *Sedum* x *rubrotinctum* had significantly higher RGR than *S. mexicanum* and *S. oxypetalum*, while *S.* x *luteoviride* and *S. stahlii* had significantly higher RGR than *S. oxypetalum* ($p<0.05$, Tukey HSD) (Figure 3.2.19).

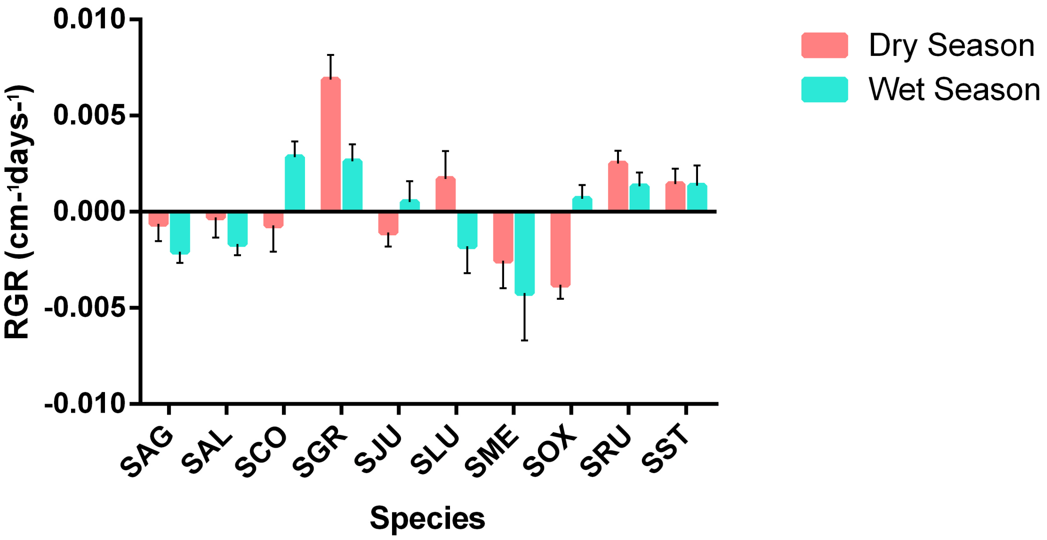


Figure 3.2.19 Relative growth rates for all species: SAG *S. allantoides* Goldii, SAL *S. allantoides,* SCO *S. confusum,* SGR *S. griseum,* SJU *S. jurgensenii,* SLU *S.* x *luteoviride,* SME *S. mexicanum,* SOX *S. oxypetalum,* SRU *S.* x *rubrotinctum* and SST *S. stahlii.* at the dry and wet planting seasons and all depths with ±SEM. Negative RGR is due to shrinking of the species during drought or due to diseases.

The above trends strongly suggest that, in terms of diameter RGR *S. griseum*, *S.* x *luteoviride*, *S.* x *rubrotinctum* and *S. stahlii* are the most suitable species for green roof planting when water is not widely available during the initial planting and establishment phase.

For the wet season established plants, the mean diameter RGR for all days and all depths showed that *S. griseum* and *S. confusum* had significantly higher RGR than *S. allantoides* Goldii, *S. allantoides*, *S.* x *luteoviride* and *S. mexicanum* ($p<0.05$, Tukey HSD) (Figure 3.2.19). *S.* x *rubrotinctum* and *S. stahlii* had significantly higher RGR than *S. allantoides* Goldii and *S. mexicanum* ($p<0.05$, Tukey HSD) (Figure 3.2.19), while *S. jurgensenii* and *S. oxypetalum* had significantly higher RGR than *S. mexicanum* ($p<0.05$, Tukey HSD) (Figure 3.2.19). This suggests that there is a high degree of variation within Mexican *Sedum* species in terms of to growth responses during the wet season, as well as to drought itself.

Differences in diameter RGR between season within species

As described in the beginning of this section and in the results per species in Section 3.2., the diameter RGR was significantly higher for the dry season established plants. The species *S. allantoides* Goldii, *S. griseum*, *S.* x *luteoviride*, *S. mexicanum*, *S.* x *rubrotinctum* and *S. stahlii* had significantly higher diameter RGR for the dry season planting ($p<0.05$, Tukey HSD) (Figure 3.2.19), while only *S. allantoides*, *S. confusum*, *S. jurgensenii* and *S. oxypetalum* had a higher diameter RGR if planted during the wet season ($p<0.05$, Tukey HSD) (Figure 3.2.19). The higher diameter RGR achieved by plants established during the dry season could be explained by the lower competition experienced by the plants in the plots which had already lower densities when water became available. This suggests that the lower densities caused by lower survival as a consequence of planting in the dry season, resulted in an assemblage containing fewer dominating species (such as *S. confusum)*, and therefore more space and nutrients were available for the smaller, less aggressive species.

Differences in RGR between depths within species

As described at the beginning of this section, depth was not a significant factor in explaining differences in plant growth rate by itself, but only in its interaction with the planting seasons. No differences between depths within species were found in the overall experiment. This may be due to the limitation of the experimental design to three replicate plots per depth and the high variability plant responses observed between these plots. Alternatively, or in addition, it could be a characteristic of the Mexican *Sedum* species studied and their habit.

Differences in RGR between depths within season by species

With respect to differences in RGR between depths within season by species, only *S. mexicanum* had a significantly higher diameter RGR at the 100 mm depth than at the 50 mm depth during the wet season ($p=0.039$, Tukey, HSD). This result demonstrates that, out of the ten *Sedums* tested, *S. mexicanum* is one of the most sensitive species to drought in terms of RGR. This could be due to the original native habitat of the plant, which is still unknown (Stephenson, 1994). Nevertheless, the possibility of rapid diameter RGR evident in this species when water is available makes it a very suitable cover plant advisable for roofs in shaded and weter areas.

3.2.3.3 Diameter

Planting season significantly affected mean diameter and, for the overall experiment, plants established during the wet season had a significantly higher mean diameter ($p<0.005$, Greenhouser-Geisser correction) (Figure 3.2.20). After day 240 the mean diameter of the wet season plants started to decrease primarily due to the on-going lack of water. By contrast, the dry season established plants' diameters increased with the onset of rain events after day 120 (Figure 3.2.20).

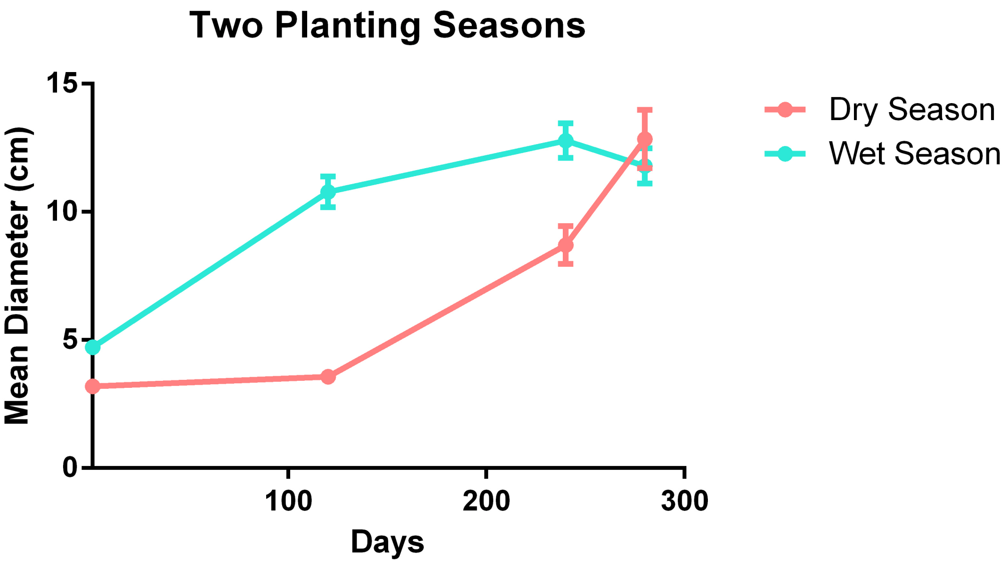


Figure 3.2.20 Mean diameters (cm), all species at all depths at two planting seasons. ±SEM bars only for between subjects.

Substrate depth significantly affected the plant mean diameters attained (p<0.005, Greenhouser-Geisser correction) (Figure 3.2.21). For the overall experiment mean diameters of plants in the 100 and 150 mm depths were significantly greater than the 50 mm depth (p<0.001, Tukey, HSD) (Figure 3.2.21).

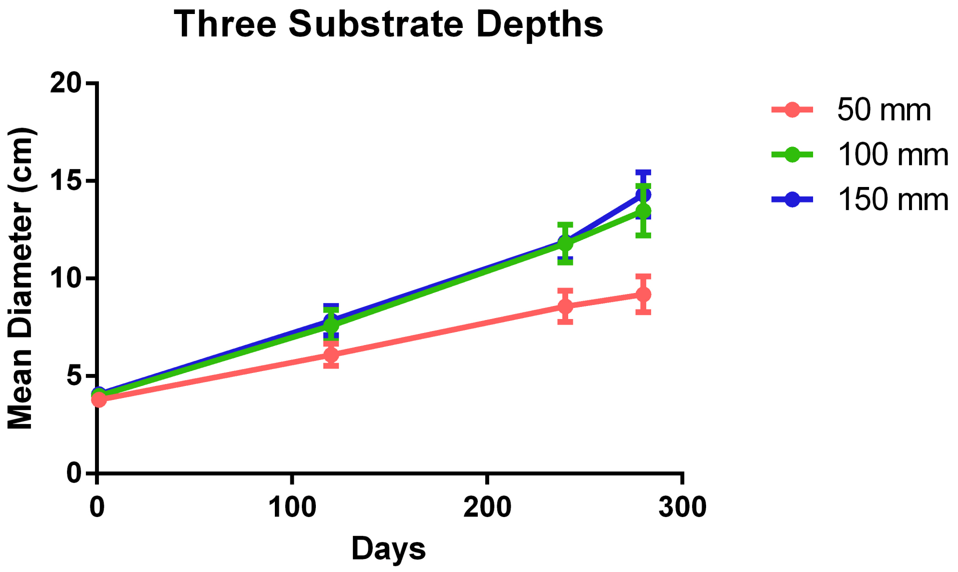


Figure 3.2.21 Diameter mean (cm) for all species in all seasons at three substrate depths. ±SEM bars only for between subjects.

During the dry planting seasons, the plants growing in the 150 and 100 mm depths had significantly higher diameters than the 50 mm depth (p<0.01, Tukey HSD) (Figure 3.2.22) and there was no significant change in the diameters of plants in the 50 mm depth over time (p>0.05) (Figure 3.2.22). In contrast plants grown in the 100 mm depth had a significant increase in diameter between days 120 and day 240 (p<0.001) (Figure 3.2.22), and the 150 mm depth plants had significantly constant increases in diameter throughout (p<0.05) (Figure 3.2.22).

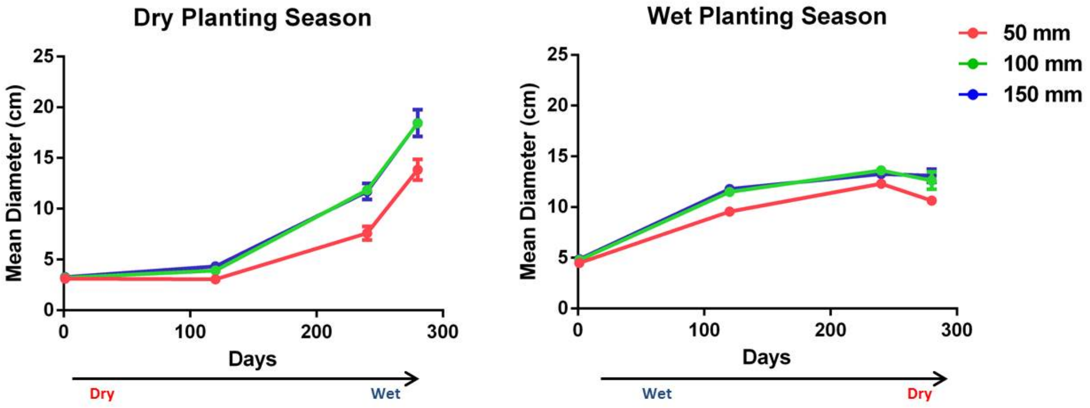


Figure 3.2.22 Repeated measures of mean diameter for dry planting season ±SEM (a) and wet planting season ±SEM (b) at three depths for all species. ±SEM bars only for between subjects.

For the wet planting season, the same pattern was observed in plants grown in the 150 and 100 mm depths, both showing significantly higher diameters than the 50 mm depth (p<0.05, Tukey HSD) (Figure 3.2.22). The 50 mm depth had a constant highly significant diameter growth up to day 240 (p<0.001), but these plants had a significant and abrupt reduction in diameter at day 280 (p<0.005) (Figure 3.2.22) after the rainy season ended. For plants grown in the 100 and 150 mm depths there were significant increases in diameter up to day 240 (p<0.05) (Figure 3.2.22) for all cases. Although plants started decrease in diameter by day 280, this change was not significant (p>0.05) (Figure 3.2.22). Under these experimental conditions it seems that the water availability during the dry and wet season is the main explanatory variable of diameter growth, and that, even though the plants of the dry season recover when rain was available, the diameter remained significantly higher for the plants of the wet season plots.

Differences in diameter between seasons within species

The differences between seasons within species showed that the only species to achieve a significantly higher mean diameter in the dry season planting were *S. allantoides* Goldii and *S. griseum* (p<0.05, Tukey HSD) as seen before in the results by species. The difference between these two highly drought tolerant species is that *S. allantoides* Goldii is a very slow-growing poorly competitive plant, while *S. griseum* proved to grow very well in the wet season plots as well. All of the species had significantly higher diameter means when established during the wet season. Species like *S. confusum* and *S. oxypetalum* presented the highest differences between seasons, with a high improvement in growth response when water became available, while species like *S. jurgensenii* and *S. mexicanum* did not respond differently between planting seasons.

Differences in diameter between depths within species

The differences between depths for the overall means shows that only *Sedum confusum* and *S. griseum* had significantly higher diameter means at 150 and 100 mm depths than at 50 mm depth ($p<0.05$, Tukey, HSD). *S. stahlii* had significantly higher diameter growth at the 150 mm depth than in the 50 mm ($p=0.024$, Tukey HSD).

Differences in diameter between depths within season by species

The only species that showed differences between depths within seasons was *Sedum confusum* which when planted at the wet season at 100 and 150 mm depths attained significantly higher mean diameters than at the 50 mm depth ($p<0.05$, Tukey HSD). For the rest of the species, differences between depths within seasons were not significant ($p>0.05$, Tukey HSD).

3.2.3.4 Height repeated measurements

The majority of the *Sedum* species in this experiment are low shrubs of 50 cm or less, with the exception of *S. oxypetalum* which can reach a meter in height when planted on the ground. The height data showed that when these short plants have sufficient water, during the wet season, the fluctuations in height are not so variable as when they are planted during the dry season. Season, therefore highly significantly affected height ($p<0.001$, Greenhouse-Geisser correction), with much taller plants resulting from wet season planting (Figure 3.2.23).

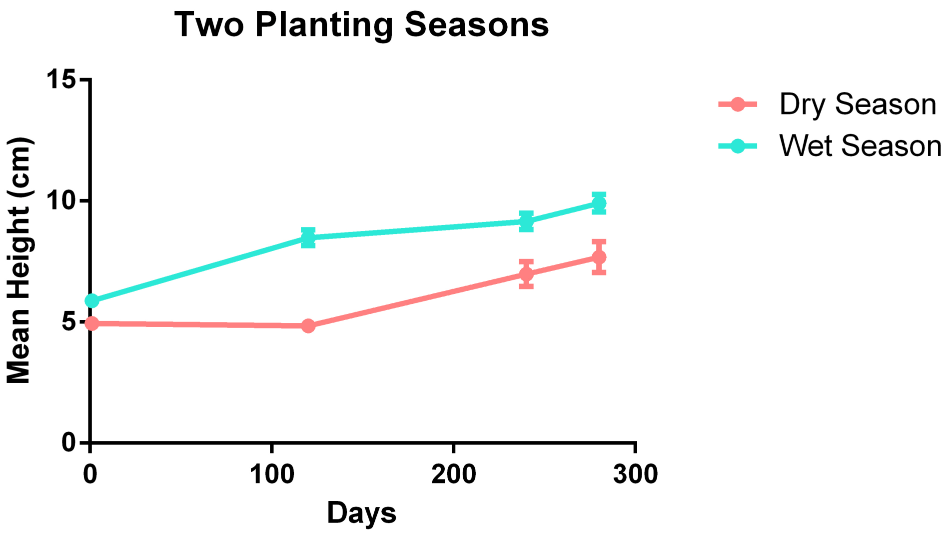


Figure 3.2.23 Repeated measures of height mean for all species and depths at two planting seasons. Initial measure of cuttings was the same for all plants before planting. ±SEM bars only for between subjects.

There was also a highly significant interaction between substrate depth and height ($p<0.001$, Greenhouse-Geisser correction). Pooled data showed that the 150 and 100 mm depths established the growth of significantly taller plants than the 50 mm depth ($p<0.05$, Tukey HSD) (Figure 3.2.24).

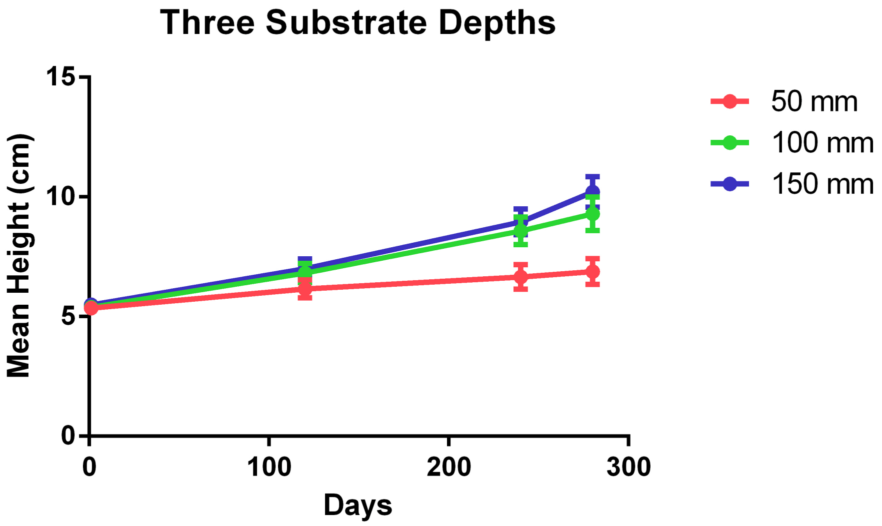


Figure 3.2.24 Repeated measures of mean height (cm), for all species and seasons at three depths ±SEM bars only for between subjects.

During the dry planting season, planting in 150 and 100 mm depths were significantly higher than the grown in 50 mm depth ($p<0.000$, Tukey HSD) (Figure 3.2.25). In comparison, during the wet season, only the 100 mm depth plants grow significantly higher than the 50 mm depth ($p=0.034$, Tukey HSD) (Figure 3.2.25).

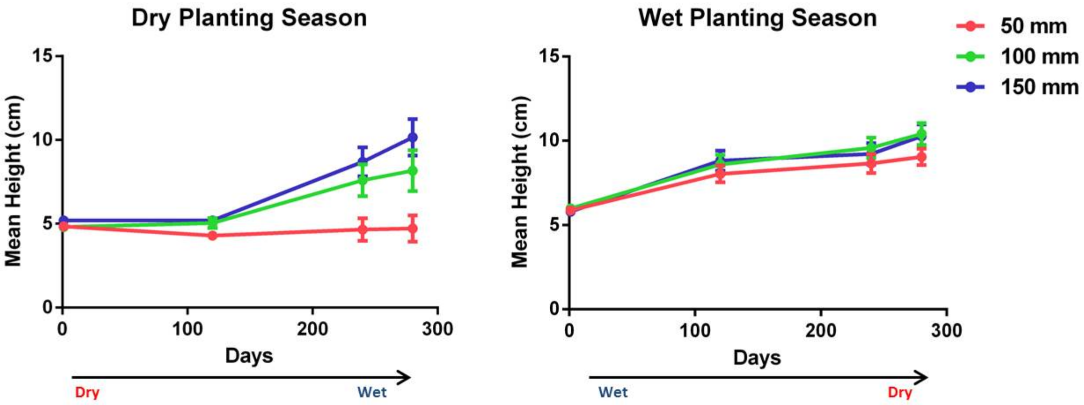


Figure 3.2.25 Repeated measures of mean height for Dry planting season ±SEM (A) and Wet planting season ±SEM (B) at three depths for all species. ±SEM bars only for between subjects.

Differences in height means between seasons within species

The mean height differences between seasons demonstrated that the only species that grew significantly taller when planted during the dry season was *Sedum allantoides* Goldii (p=0.005, Tukey HSD). The species *S. confusum*, *S. griseum*, *S. jurgensenii*, *S. oxypetalum* and *S.* x *rubrotinctum* all grew significantly taller when planted in the wet season (all p<0.05, Tukey HSD). The species *S.* x *luteoviride*, *S. mexicanum*, *S. allantoides* and *S. stahlii* did not show any significant height differences between seasons (p>0.05, Tukey HSD). The observation that species like *S. confusum*, *S. jurgensenii* and especially *S. oxypetalum* displayed large differences in height between planting season experiments, in a similar manner to their changes in diameter, strongly suggests that these species are particularly sensitive to water availability during establishment.

Differences in height mean between depths within species

There were only three species that presented significant height differences between depths. *S. confusum* grew significantly taller in the 150 and 100 mm depths than in the 50 mm depth (p<0.050, p=0.011 respectively, Tukey HSD). Lastly, *S.* x *rubrotinctum* was significantly higher in the 100 mm depth compared to the 50 mm depth (p=0.045, Tukey HSD). *S. confusum* followed the same pattern in height as it did in the diameter analyses, while *S. griseum* showed differences only between the 150 and 50 mm depth. *S.* x *rubrotinctum* did not show significant differences in diameter between depths, and it possessed almost the same mean diameter between the 150 mm and the 100 mm. However, *S.* x *rubrotinctum* grew taller in the 100 mm depth than in both the 50 mm depth and the 150 mm depth as well. This response could be caused by an interaction between water availability and competitors; with the higher amount of water in the 100 mm than in the 50 and the lower competition in the 100 mm substrate in comparison with the 150 mm depth.

Differences in height between depths within season by species

There were few significant differences in height between depths within seasons by species. Dry season established *S. griseum* grew significantly taller in the 150 mm depth than in the 50 mm depth (p=0.018, Tukey HSD) and *S.* x *rubrotinctum* grew significantly higher in the 100 mm depth than in the 50 mm depth (p=0.039, Tukey HSD). Interestingly, and in strong contrast, the wet season established *S.* x *rubrotinctum* grew significantly taller in the 50 mm depth than at the 150 and 100 mm depths (p<0.05, Tukey HSD). These responses of *S.* x *rubrotinctum* might also be related to the interplay between the availability of water and competition. In the dry season, the 100 mm depth hold more water and plants were able to grow more than in the 50 mm depth, but the competition in the 150 mm depth (where water availability was even higher) restricted establishment and individual growth. The reverse mechanism may have been at play for wet season established plants, where individuals in the 50 mm depth had less competition with other species than in the 100 and 150 mm depth, and plants that could cope with the shallower substrate and reduced water availability were able to grow taller.

3.3 Extended results of 10 Sedum species in three substrate depths over the growing seasons

As described in the Chapter 3 introduction, this section presents the results for the dataset corresponding to the wet planting season over the course of a 17 month period- extending across a total of three growing seasons. The majority of the measurements were performed on a monthly basis, with the exception of the last four that were performed at days 280, 330, 36 and 460.

3.3.1 Temperature and precipitation

Mexico City's Cwb climate, coupled with its mean elevation of 2240 m, results in annual extremes of temperature and precipitation. This experiment was initiated during the second week of July 2011 and it was harvested in the third week of November of 2012. Overall, during the 17 months of the experiment the mean precipitation was 59.76 mm and the total accumulated precipitation was 1075.7 mm (Figure 3.3.1 A).

The months with the minimum precipitation were December 2011 (Day 150) with 0.9 mm in the entire month, and, the next year, in October 2012 (Day 460) with 17 mm over the month (Figure 3.3.1 A). The highest precipitation in 2011 was during July and August (Day 1 to 45), with 230.5 and 158.9 mm per month, respectively, and in 2012 in the same months with 160.5 and 108.4 mm (Figure 3.3.1 A). The mean temperature during the experiment was 17.01 °C, with a mean maximum temperature of 23.64 °C, and a mean minimum temperature of 10.68 °C. The highest mean maximum temperature was registered during 2011 in August (Day 40) with 24.5 °C and for 2012 in May (Day 300) with 27 °C (Figure 3.3.1 B). The lowest mean minimum temperatures in 2011 occurred in December (Day 150) with 6.3 °C, and in 2012 in November (Day 470) with 12.7 °C (Figure 3.3.1 B).

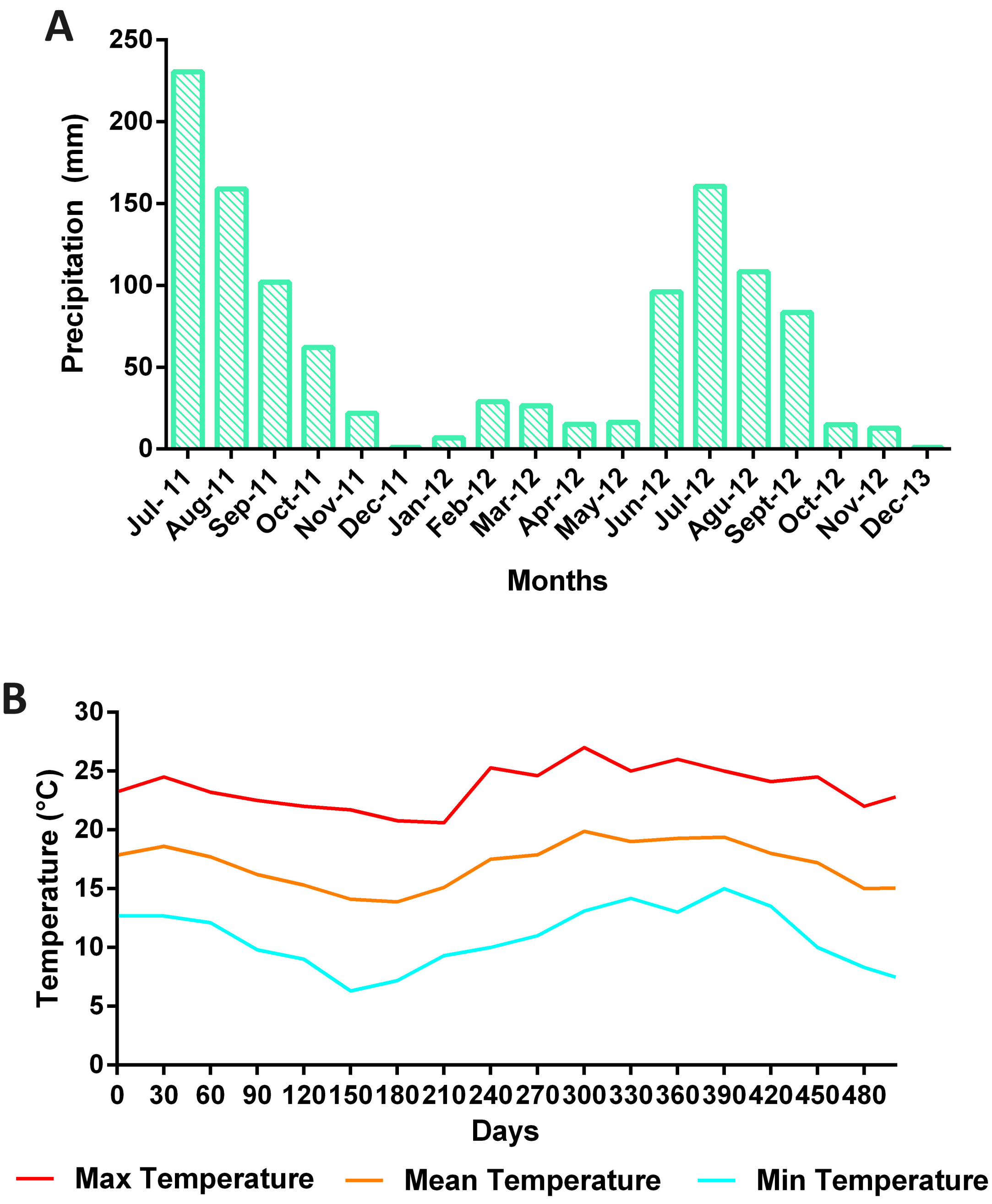


Figure 3.3.1 A) Precipitation (mm) B) mean, maximum and minimum for Mexico City from July 2011 (Day 1) to Dec 2013 (Day 480) based on (SMN-México, 2014).

3.3.2 Results per species

3.3.2.1 Sedum allantoides Goldii

Sedum allantoides Goldii (Figure 3.3.2 A) survival rates, diameter relative growth rate, diameter and height were not significantly affected by depth (p>0.05, Greenhouse-Geisser correction) (Figure 3.3.2 B,C,D and E). Nevertheless, plants of *S. allantoides* Goldii had problems with fungal infections during the rainy season. This could be related to the highly succulent stems of this species, which split open their cuticle when excess uptake of water causes tissue swelling and bursting. The resulting sites of injury may become sites of fungal attack. *S. allantoides* Goldii proved to be a very slow growing plant (Figure 3.3.2 C, D, and E). The percentage cover achieved by this plant was one of the lowest of all the species tested, with no significant differences between depths (p>0.05). The percentage of *S. allantoides* Goldii plants in flower was as low as 6% in the 100 and 150 mm depths during the months of May, June and July, with no flowers whatsoever in the 50 mm depth. Flowering was not significantly different (p>0.05, Greenhouse-Geisser, correction) (Figure 3.3.2 F) between 100 and 150 mm depths, but the complete absence of flowers in the 50 mm plots strongly suggests that substrate depth may have played a major role in the overall poor performance of this species. However, *Sedum allantoides* Goldii is a plant that grows in very arid environments, especially on rocks, with very low competition from other species. For this reason, its slow responses may have be caused by an interaction with substrate depth and another factor or factors such as interspecies competition. It is possible that this stress tolerant plant grows better in monocultures or in combination with other slow growing species and in a substrate with good drainage but constant water during the summer.

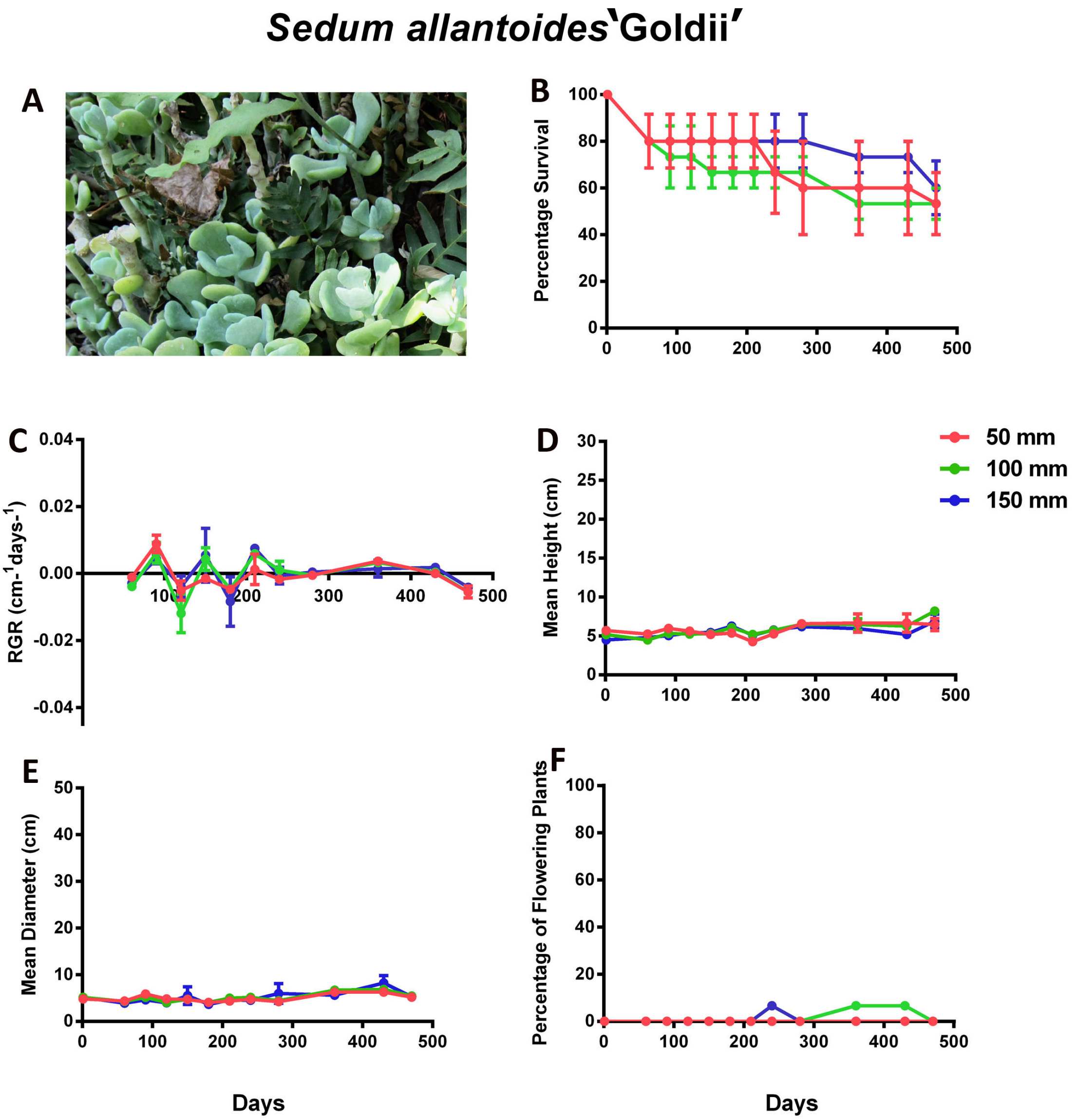


Figure 3.3.2 A) *S. allantoides* 'Goldi' Repeated measures at three depths of: B) Percentage survival, C) Diameter Relative Growth Rate, D) Mean Height, E) Mean Diameter, F) Percentage of flowering plants. ±SEM bars only for between depths subjects. Negative RGR is due to shrinking of the species during drought or due to diseases.

3.3.2.2 *Sedum allantoides*

The survival, diameter relative growth rate, diameter, and height of *Sedum allantoides* (Figure 3.3.3 A) were not affected by depth of substrate (p>0.05, Greenhouse-Geisser correction) (Figure 3.3.3 B,C,D and E). It is evident that there was however, a clear and unexpected trend in the percentage survival between treatments. The 100 mm depth plants experienced the greatest mortality and 150 mm achieved the lowest. This could be the result, as well, of the initial fungal infection. There were no significant differences in final percentage cover of *S. allantoides* between depths (p>0.05). The percentage of flowering plants did not differ significantly between depths (p>0.05, Greenhouse-Geisser correction). At day 210 the peak of the flowering period occurred for this species, equivalent to the month of December (Figure 3.3.3 F).

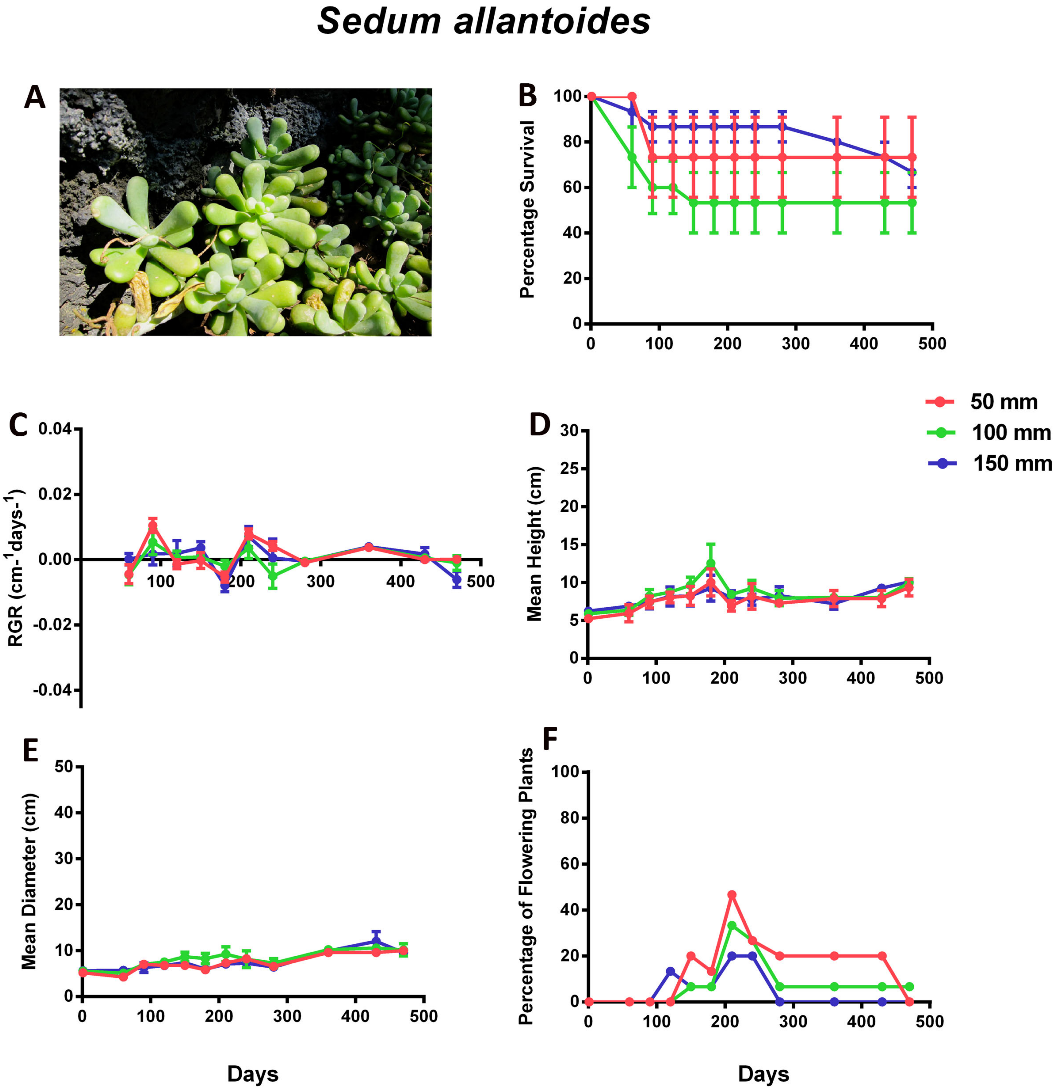


Figure 3.3.3 A) *S. allantoides*, Repeated measures at three depths of: B) Percentage survival, C) Diameter Relative Growth Rate, D) Mean Height, E) Mean Diameter, F) Percentage of flowering plants. ±SEM bars only for between depths subjects. Negative RGR is due to shrinking of the species during drought or diseases.

3.3.2.3 *Sedum confusum*

Sedum confusum (Figure 3.3.4 A) survival, diameter RGR, and height were not affected significantly by substrate depth ($p>0.05$, Greenhouse-Geisser correction) (Figure 3.3.4 B, C and D). The changes of diameter over time were highly significant ($p<0.000$, Greenhouse-Geisser correction) and depth significantly affected the diameter achieved by the plants ($p<0.05$, Greenhouse-Geisser correction), (Figure 3.3.4 E). Depths 150 and 100 resulted in significantly taller plants than the 50 mm depth ($p<0.05$, Tukey HSD). The percentage cover of *S. confusum* was significantly affected by substrate depth ($p<0.50$), where the 150 mm depth ended with significantly greater coverage than the 50 mm depth ($p<0.05$, Tukey HSD). Only 6% of the plants of *S. confusum* flowered during the whole experiment, and only in the 100 mm depth, during January and August (Days 240 and 474).

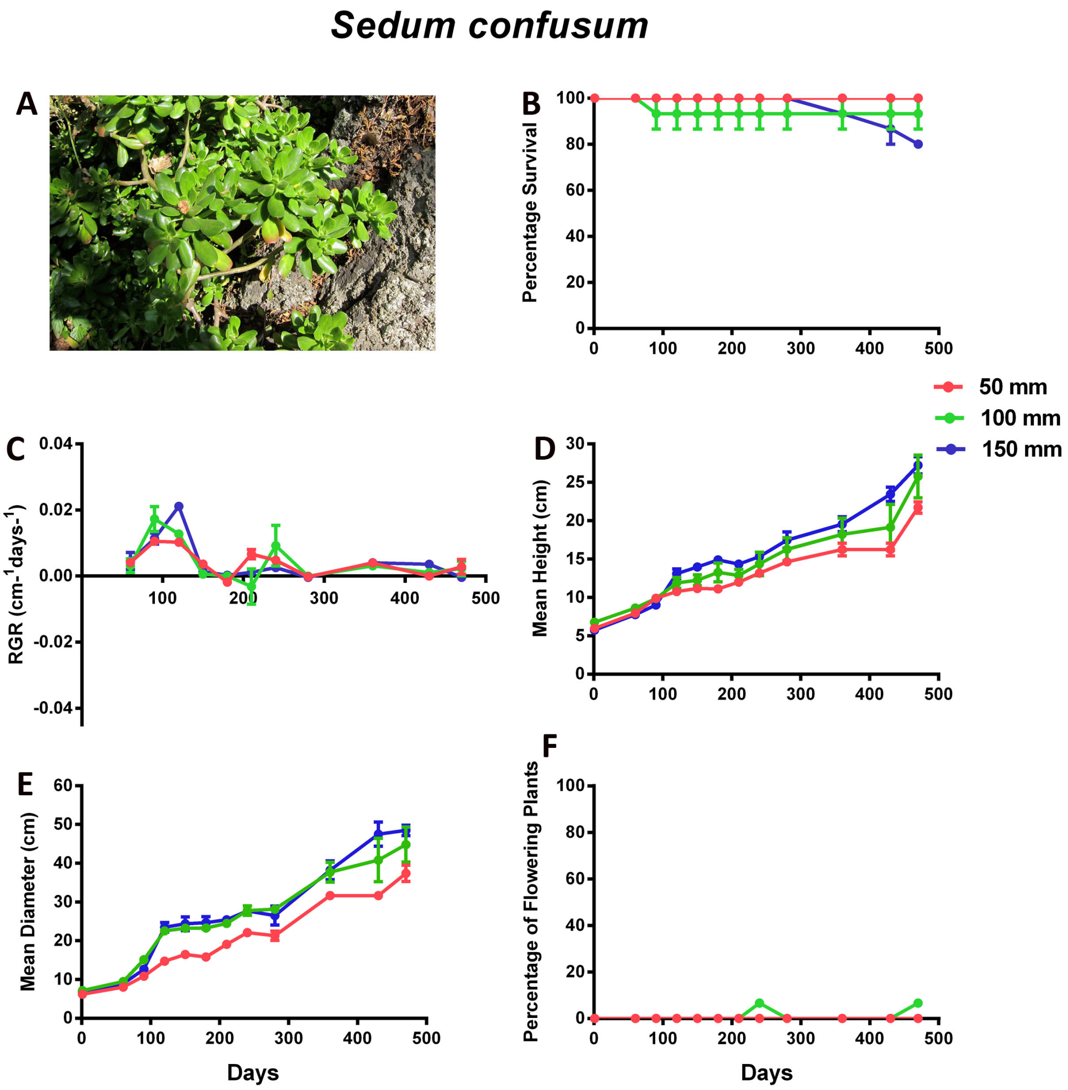


Figure 3.3.4 A) *S. confusum*, Repeated measures at three depths of: B) Percentage survival, C) Diameter Relative Growth Rate, D) Mean Height, E) Mean Diameter, F) Percentage of flowering plants. ±SEM bars only for between depths subjects. Negative RGR is due to shrinking of the species during drought or diseases.

S. confusum species is a stress tolerant plant that has some characteristics of a competitive species. It showed significant growth response differences between depths, probably due to variations in water availability, with a greater vigour at the 100 and 150 mm depth, and poor performance in the 50 mm depth. Although no total leaves count was performed in this experiment, it was observed that the greater the depth of substrate the higher the amount of leaves the plants had, and lack of water at the 50 mm depth during the drought periods, led the plants to drop leaves and look very leggy. This species is good for a planting in a minimum of 100 mm depth, but due to its high vigour, if other smaller *Sedum* species want to be grown it is advisable to plant *S. confusum* in lower densities.

3.3.2.4 Sedum griseum

Sedum griseum (Figure 3.3.5 A) did not respond significantly differently in growth between depths for any parameter (p>0.05, Greenhouse-Geisser correction) (Figure 3.3.5 B,C,D, E and F). There were several flowering periods: the first one during the summer from day 60 to day 120, equivalent to July to September; the next flowers appeared in December and January (days 210 and 240), and finally, new flowers appeared during May and July (Days 369 to 429) (Figure 3.3.5 F). Hints of these different flowering times have been reported in the literature before, for, in the wild, plants in bud were found during September and flowers and buds have been reported during December (Clausen, 1959).

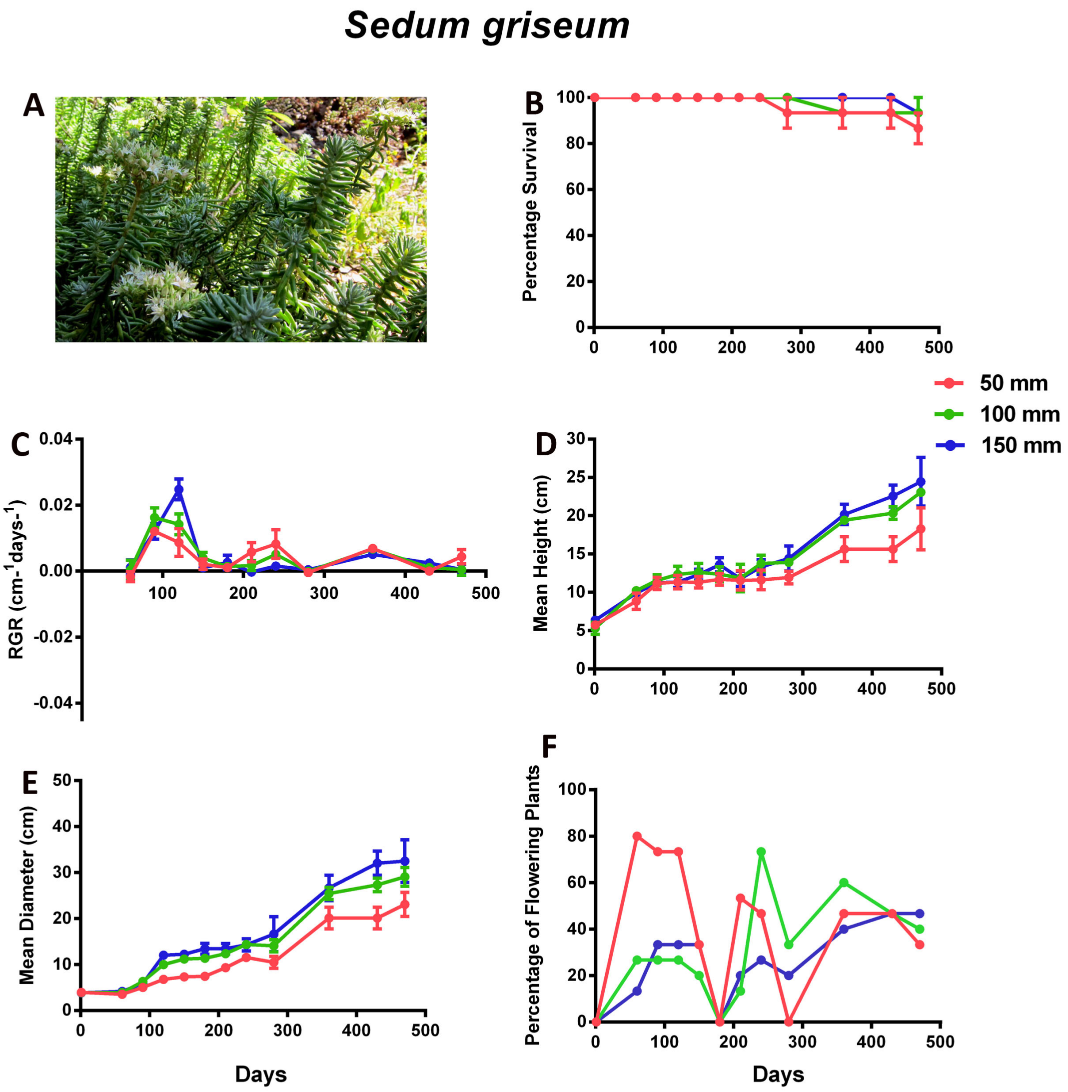


Figure 3.3.5 A) *S. griseum*, Repeated measures at three depths of: B) Percentage survival, C) Diameter Relative Growth Rate, D) Mean Height, E) Mean Diameter, F) Percentage of flowering plants. ±SEM bars only for between depths subjects. Negative RGR is due to shrinking of the species during drought or diseases.

Sedum griseum had the best performance of all species during the experiment. Even though this stress tolerant plant has some competitive attributes, it does not compare with *S. confusum* and, can have a better performance in more stressful conditions, like the 50 mm depth, and as seen in the previous section during the dry planting season as well. The plant produces a high quantity of flowers. Nevertheless, it can become leggy after severe drought when the plant loses leaves, and therefore some pruning is advisable to keep plants in shape.

3.3.2.5 Sedum jurgensenii ssp. jurgensenii

For *Sedum jurgensenii* (Figure 3.3.6 A) none of the growth parameters were significantly affected by depth (p>0.05, Greenhouse-Geisser correction) (Figure 3.3.6 B,C,D,E and F). The plants of *Sedum jurgensenii* flowered in the 150 and the 50 mm depth during summer, around day 90, and during winter around day 210. For the 100 mm depth, although some plants flowered in late winter, most of the plants flowered during the summer Figure 3.3.6 F). This species, native to the Pedregal of San Angel, the exact area where the plots were set up, did not display very vigorous growth during the experiment; nevertheless it had a constant growth in diameter. Aesthetically, it does not present many unique attributes but as a native species with a declining habitat, the roofs can become a potential refuge for the species.

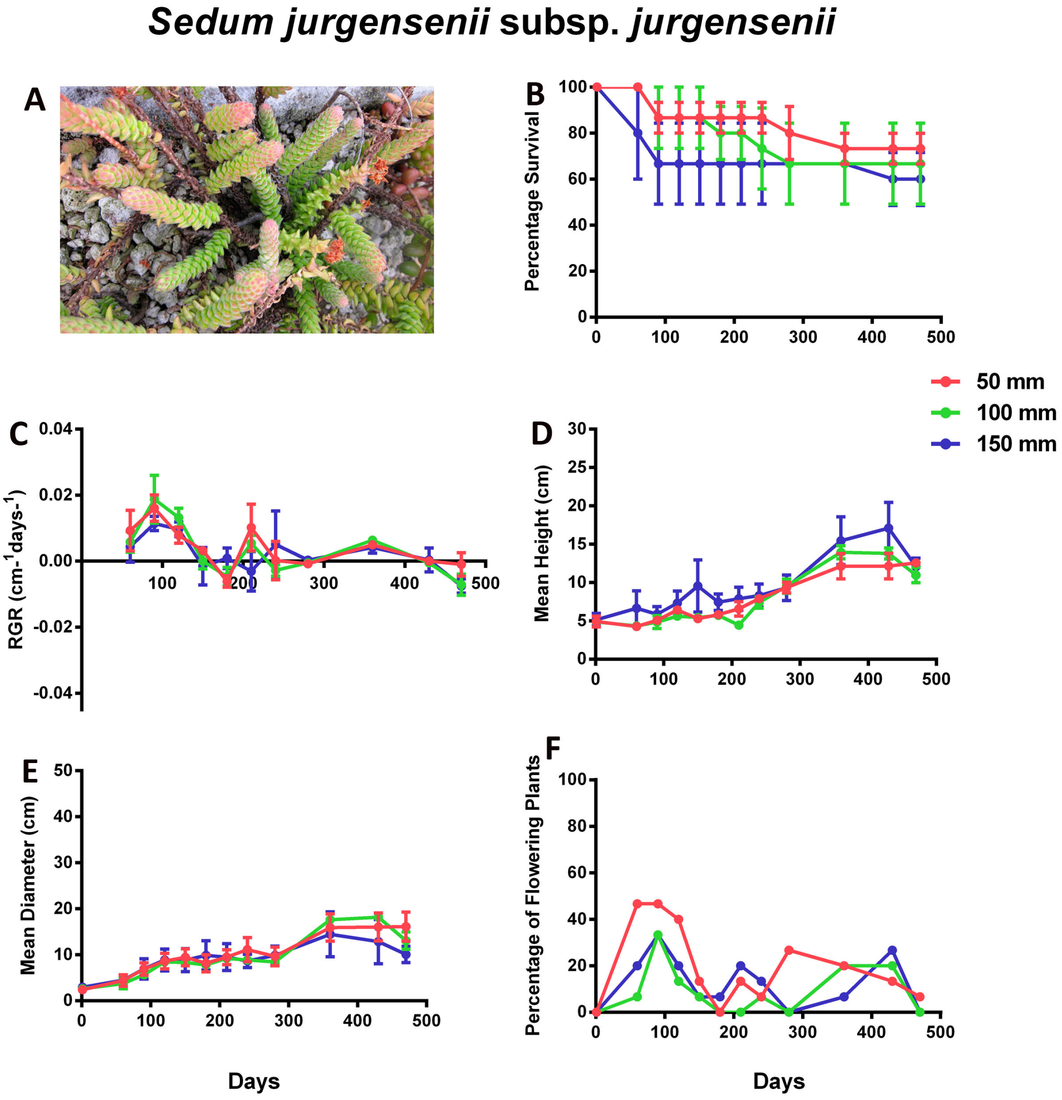


Figure 3.3.6 A) *S. jurgensenii* subsp. *jurgensenii*, Repeated measures at three depths of: B) Percentage survival, C) Diameter Relative Growth Rate, D) Mean Height, E) Mean Diameter, F) Percentage of flowering plants. ±SEM bars only for between depths subjects. Negative RGR is due to shrinking of the species during drought or diseases.

3.3.2.6 Sedum x *luteoviride*

The survival and diameter relative growth rate of *Sedum* x *luteoviride* (Figure 3.3.7 A) did not differ significantly between depths ($p>0.05$, Greenhouse-Geisser correction), however it is evident from the data that survived was best for plants grown in 50 mm substrate (Figure 3.3.7 B and C). Depth significantly affected diameter ($p<0.01$ Greenhouse-Geisser correction) (Figure 3.3.7 E), but it was not possible to see which depth affected growth the most since the post hoc did not have enough power. Plants started to lose side branches, which dried around the nodes and fell to the ground. This seems to be a method of vegetative propagation, although only a very small proportion of the stems successfully rooted on the ground (Figure 3.3.7 E). This habit may explain the massive reduction in diameters in 100 and 150 mm depth plants, which was absent from the 50 mm depth plants, which may not have grown tall enough for this.

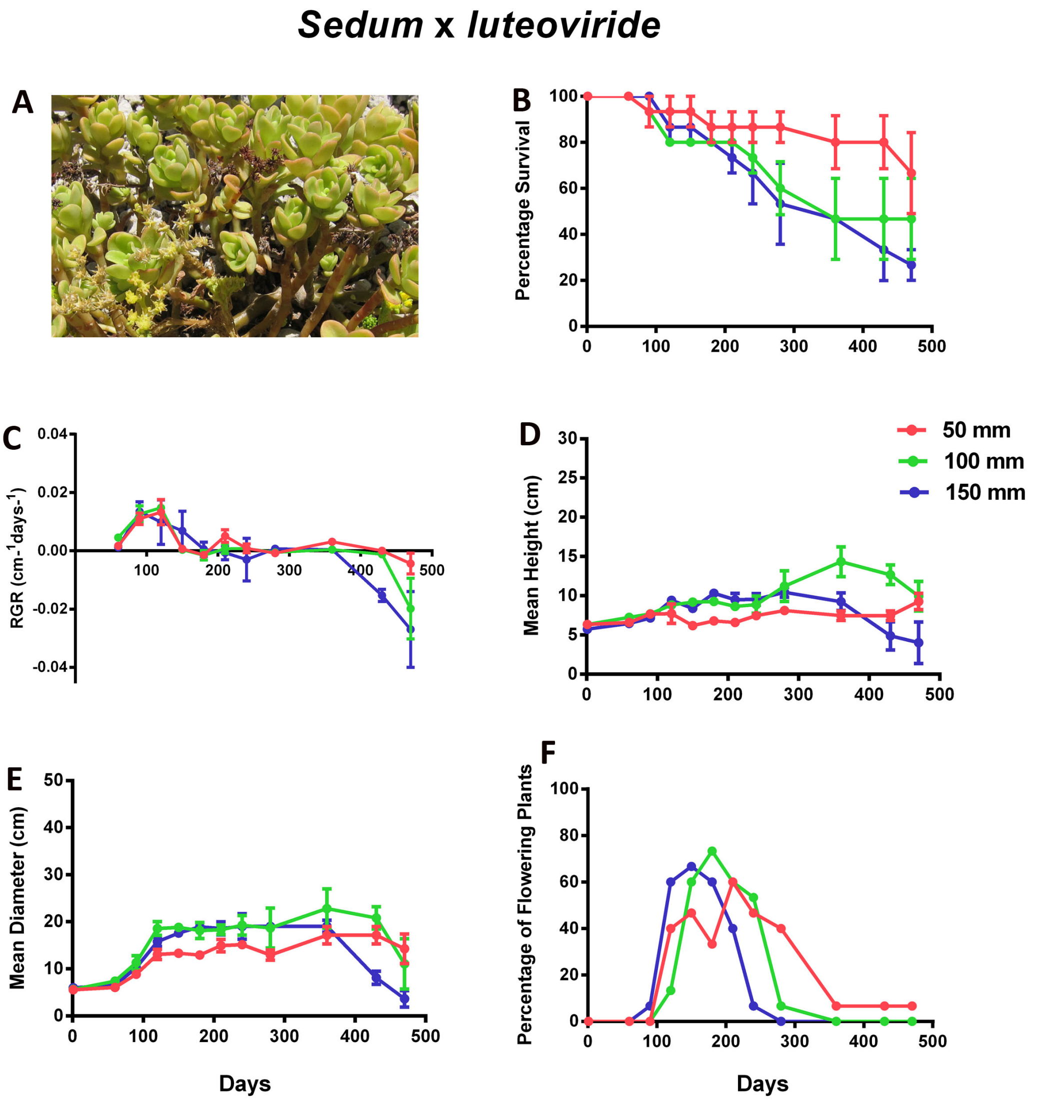


Figure 3.3.7 A) *S.* x *luteoviride,* Repeated measures at three depths of: B) Percentage survival, C) Diameter Relative Growth Rate, D) Mean Height, E) Mean Diameter, F) Percentage of flowering plants. ±SEM bars only for between depths subjects. Negative RGR is due to shrinking of the species during drought or diseases.

Depth significantly affected height (p=0.031, Greenhouse-Geisser correction). Nevertheless, in this case it was not possible to ascertain in which depths lay the significant differences, but plants grew taller in 100 mm, before die-back reduced them to the same height as those growing in 50 mm substrate (Figure 3.3.7 E). The percentage cover did not present any significant differences between depths (p>0.05) although there was a trend of a higher percentage cover at the 50 mm depth. The percentage of flowering plants of *S.* x *luteoviride* was not significantly affected by depth (p>0.05, Greenhouse-Geisser correction). The flowering time was distributed mainly during summer for the three depths, although the flowering period of the 50 mm depth extended until February (Day 270) (Figure 3.3.7 F). Perhaps due to the harsh environment of the 50 mm depth retarding the seed production. It is evident that plants in the 150 mm had the worst performance in almost all parameters, especially from day 360 after the drought, when water became available. This might be caused by the competition from plants such as *S. confusum* and *S. griseum.*

3.3.2.7 *Sedum mexicanum*

Sedum mexicanum (Figure 3.3.8 A) was not affected by depth in any parameter (i.e. survival, diameter relative growth rate, diameter, height, or percentage of flowering plants) ($p>0.05$, Greenhouse-Geisser correction) (Figure 3.3.8 B, C, D, E and F). The percentage of flowering plants of the 50 and 100 mm depths had their peak during winter from January to February (Day 240 to Day 270). In contrast, the 150 mm depth plants also started flowering in January (Day 240), but the peak of the flowering period extended until May (Day 368) (Figure 3.3.8 F).

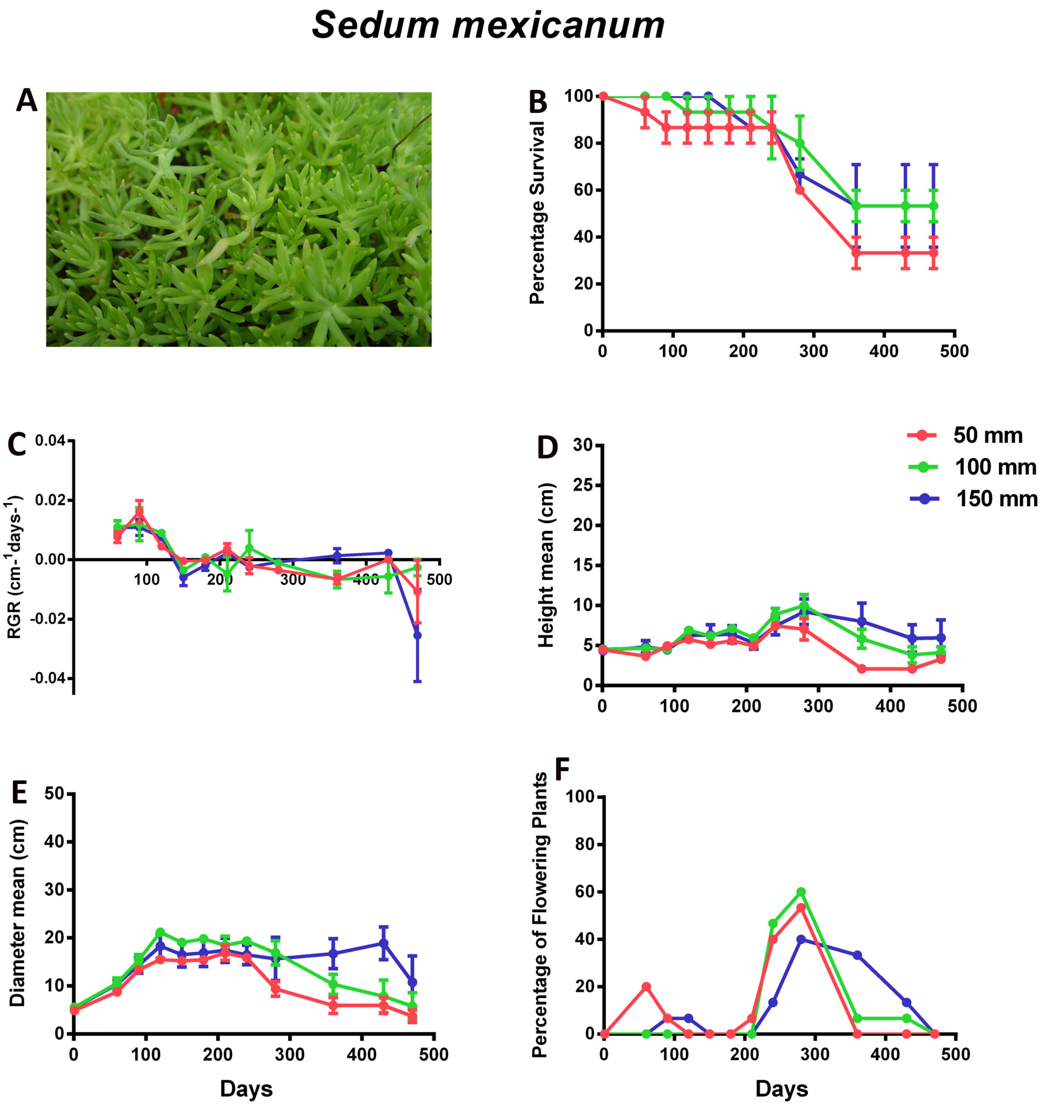


Figure 3.3.8 A) *S. mexicanum* Repeated measures at three depths of: B) Percentage survival, C) Diameter Relative Growth Rate, D) Mean Height, E) Mean Diameter, F) Percentage of flowering plants. ±SEM bars only for between depths subjects. Negative RGR is due to shrinking of the species during drought or diseases.

Interestingly although this species behaves as a perennial when cultivated on ground level, at the roof level behaves as an annual due to the extreme solar radiation and the drought. If the plants of *S. mexicanum* can not find a shade or if there is not enough water available, they can dehydrate very fast and burn. This sensitivity to drought makes it a bad ground cover plant by itself, since it can grow fast when water is available and die back rapidly during droughts, leaving big gaps on the substrate surface. If it is mixed with bigger species that can provide some shade, and if it is watered during the driest months, it can add an extra layer to the plant community and help to reduce weeds.

3.3.2.8 Sedum oxypetalum

Substrate depth did not affect *Sedum oxypetalum* (Figure 3.3.9 A) in any parameter (p>0.05, Greenhouse-Geisser correction) (Figure 3.3.9 B, C, D, E and F). The peak flowering period occurred during the summer in August (Day 60 to Day 90), as the available literature reports it does in the wild (Clausen, 1959), and as found in local populations in the Pedregal de San Angel. Nevertheless during the second summer only a small percentage of plants flowered. If in a longer study it is observed that plants can flower their usual quantities in the roof environment it is recommended to be use as an accent plant. It is constantly visited by bees and the firm branches of *S. oxypetalum* can function as perches for birds. Since the roots are superficial, there is no risk of damage to the underlying roof. Cuttings need to be planted with enough water available in order to root.

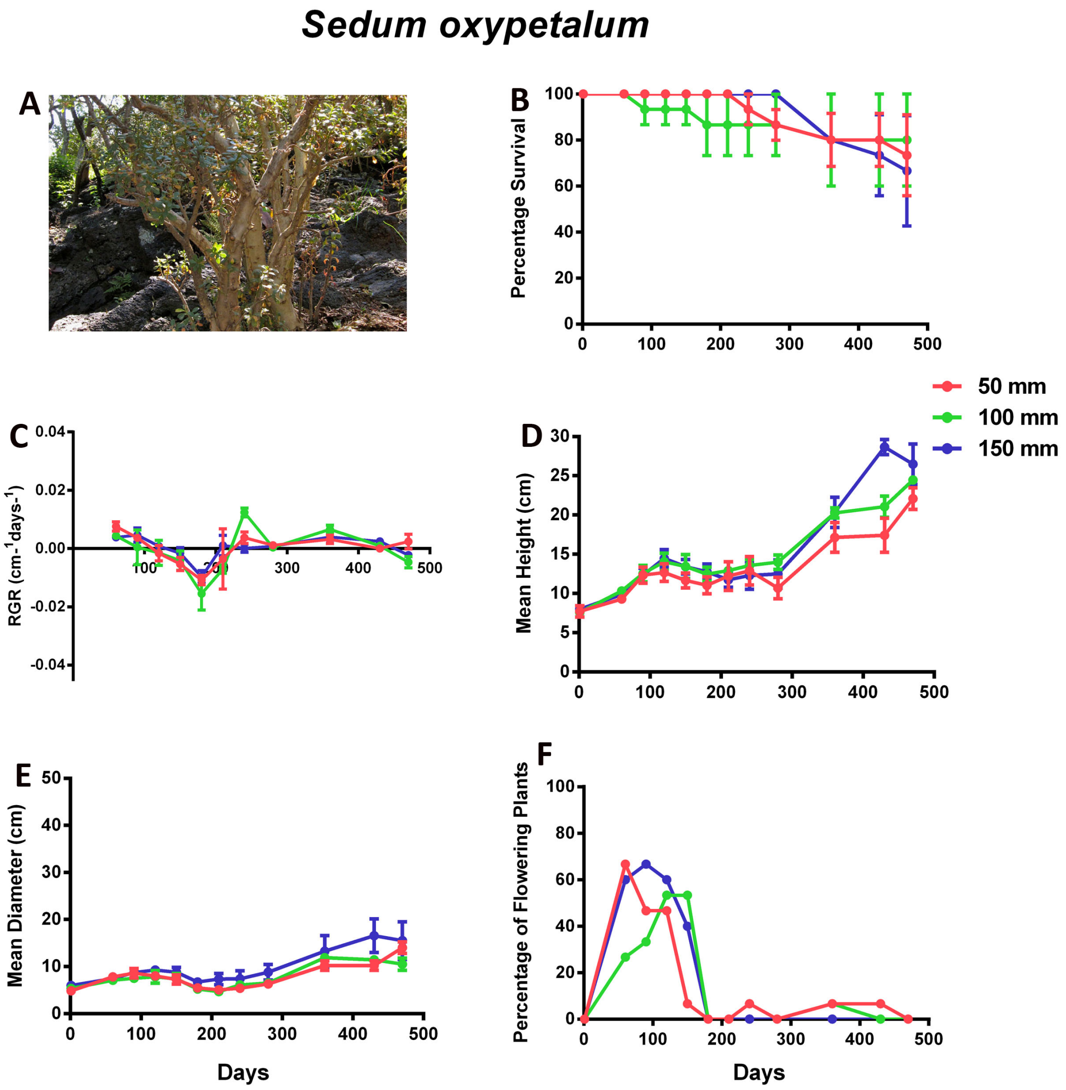


Figure 3.3.9 A) *S. oxypetalum*, Repeated measures at three depths of: B) Percentage survival, C) Diameter Relative Growth Rate, D) Mean Height, E) Mean Diameter, F) Percentage of flowering plants. ±SEM bars only for between depths subjects. Negative RGR is due to shrinking of the species during drought or diseases.

3.3.2.9 Sedum x *rubrotinctum*

Sedum x *rubrotinctum* (Figure 3.3.10 A) was not significantly affected by substrate depth at any parameter ($p>0.05$, Greenhouse-Geisser correction) (Figure 3.3.10 B, C, D, E and F). Percentage cover was not significantly different between depths ($p>0.05$). The peak of the flowering period was during winter in December, January and February (Days 210, 240 and 270) (Figure 3.3.10 F). There was a tendency for a higher number of flowering plants in the 100 mm depth. The overall performance of *S.* x *rubrotinctum* was very good. This species has a high survival and a steady growth. Although it is not as vigorous as *S. confusum*, it is less sensitive to drought, so it can grow well in shallow substrates of 50 mm depth. Its red leaf tips and spiral phyllotaxy provides unique colour and texture to the Mexican green roof palette.

Sedum* x *rubrotinctum

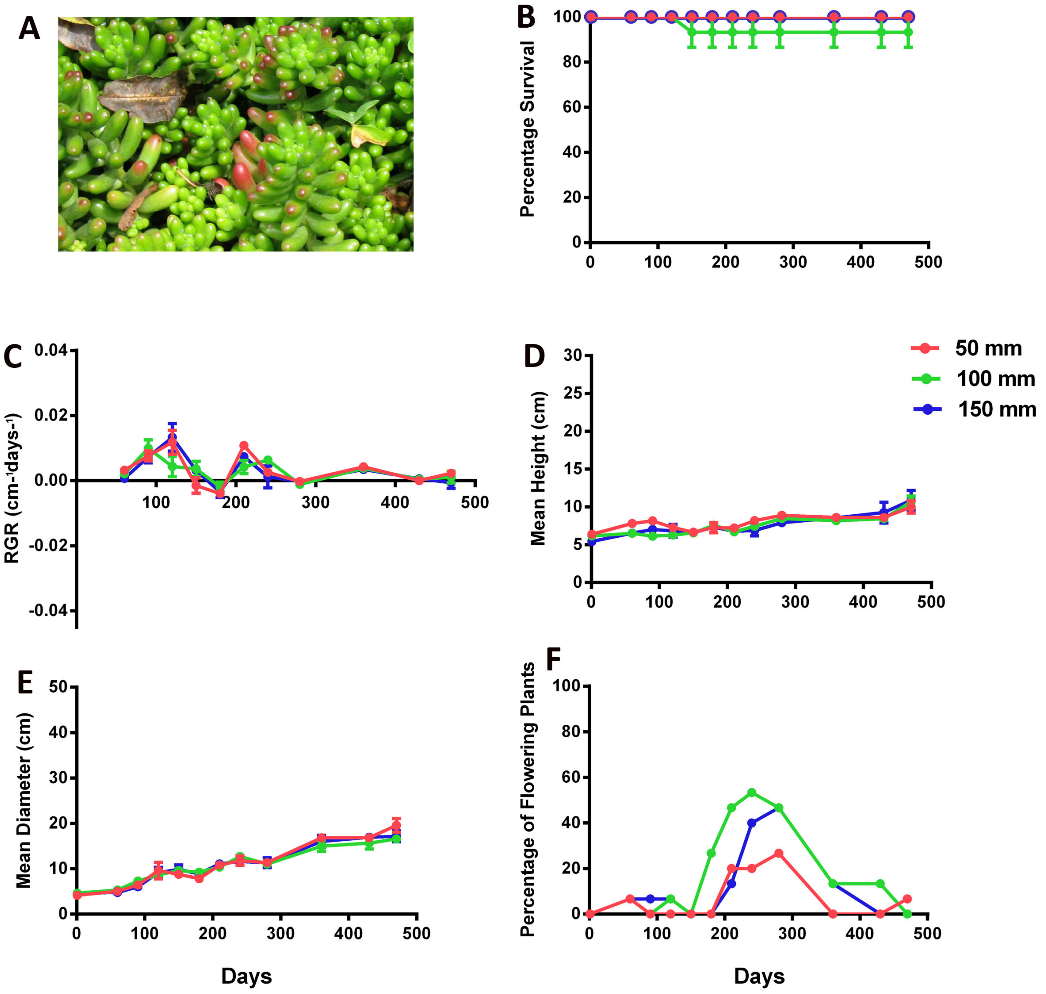


Figure 3.3.10 A) *S.* x *rubrotinctum*, Repeated measures at three depths of: B) Percentage survival, C) Diameter Relative Growth Rate, D) Mean Height, E) Mean Diameter, F) Percentage of flowering plants. ±SEM bars only for between depths subjects. Negative RGR is due to shrinking of the species during drought or diseases.

3.3.2.10 Sedum stahlii

The survival, diameter relative growth rate, diameter, and height of *Sedum stahlii* (Figure 3.3.11 A) were not significantly affected by substrate depth ($p>0.005$, Greenhouse-Geisser correction) (Figure 3.3.11 B, C, D and E). The percentage cover of *Sedum stahlii* was significantly affected by depth ($p<0.05$), where the 150 mm depth plants grew significantly more than those in the 50 and 100 mm depth ($p<0.01$, Tukey HSD). This might be due to a higher number of successful rooted leaves in the 150 mm depth because of a greater moisture availability. The percentage of flowering plants was not significantly affected by substrate depths ($p>0.05$, Greenhouse-Geisser correction). The main flowering months of this species were from January to February (Days 240 and 270) (Figure 3.3.11 F).

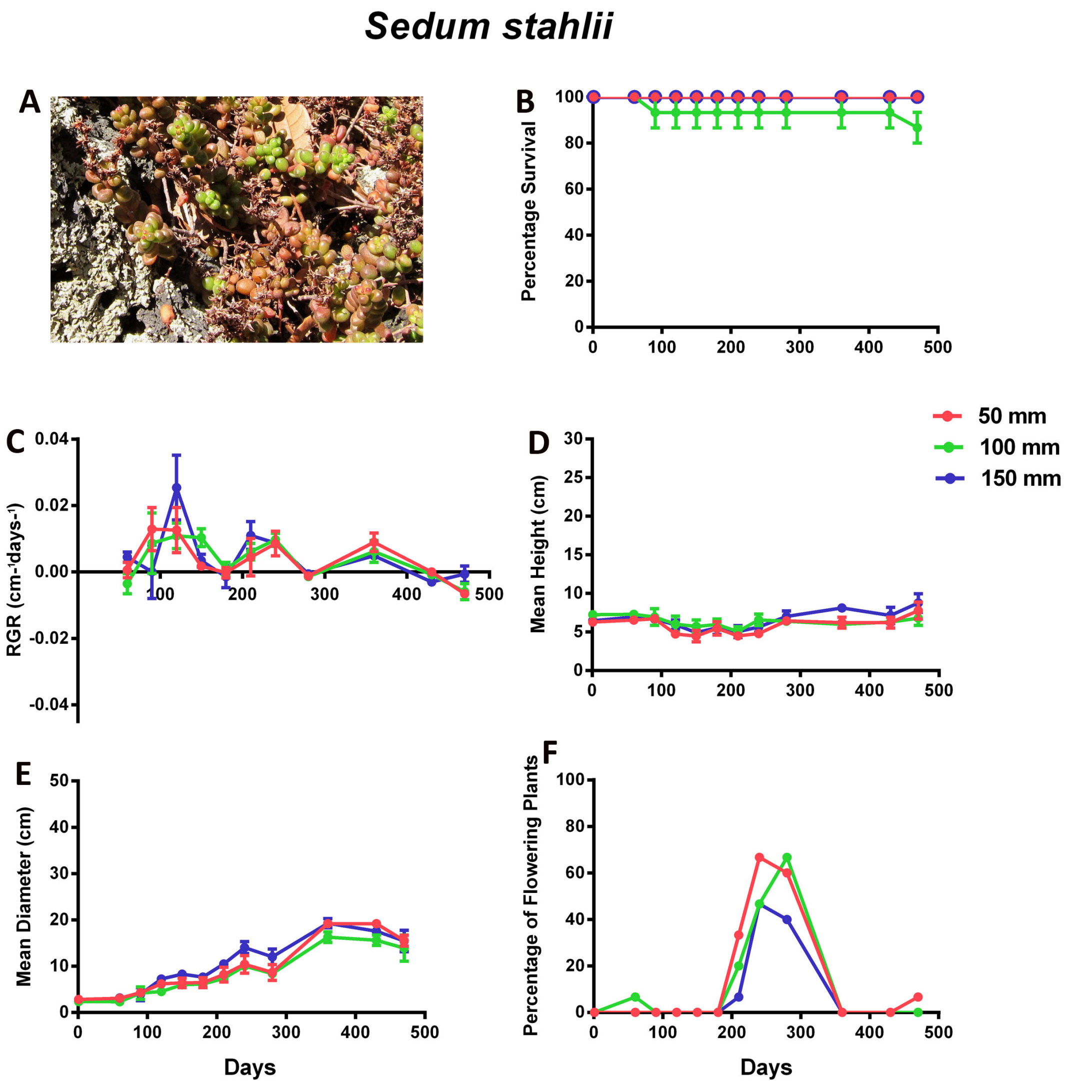


Figure 3.3.11 A) *S. stahlii*, Repeated measures at three depths of: B) Percentage survival, C) Diameter Relative Growth Rate, D) Mean Height, E) Mean Diameter, F) Percentage of flowering plants. ±SEM bars only for between depths subjects. Negative RGR is due to shrinking of the species during drought or diseases.

S. stahlii does not present very remarkable aesthetic qualities and a very low proportion of plants flowered. Nevertheless, the species could be used in green roof plant communities in Cwb climates to help provide some cover and protect the substrate from weeds. One of the best qualities of this species is that the fallen leaves can root very easily and form new plants. The cover % was higher at the 150 mm, where plants not only grew bigger, but more leaves were able to root. It is necessary to point out that if not advisable to use this species as a single cover plant since it is not so vigorous, and the easily detachable leaves that help its vegetative propagation can make it leggy at times.

3.3.3 Results for pool species at 3 depths

3.3.3.1 Survival

Depth alone did not significantly affect the overall survival of the species (p=0.108, Greenhouse-Geisser correction) (Figure 3.3.12), while the species did (p<0.001, Tukey HSD)

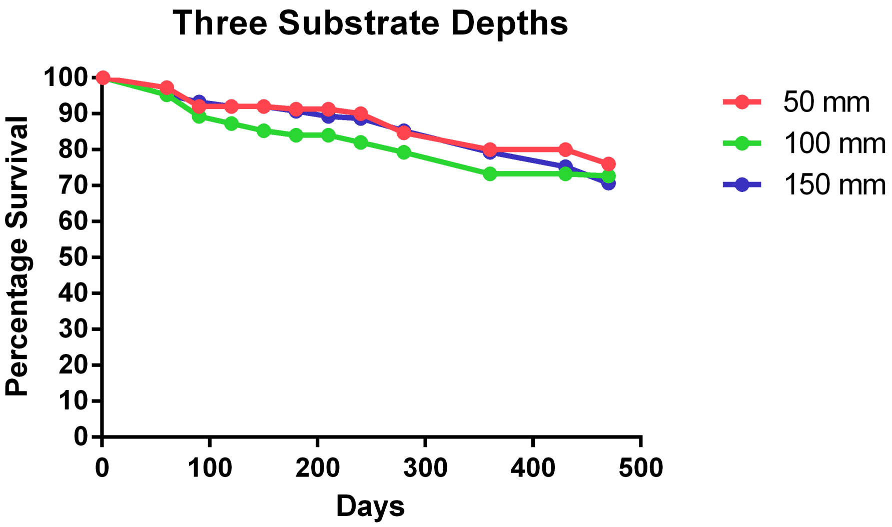


Figure 3.3.12 Mean percentage survival of all species at three depths. ±SEM bars only for between subjects.

Survival at 50 mm depth

Even if not significant, it is worth noting that at the end of the experiment the 50 mm depth had a higher survival than that of the 100 mm and 150 mm (Figure 3.3.12). This could be explained by the high competitiveness of some plants in the deeper substrates with vigorous species such as *S. confusum* and *S. griseum* in particular. For the 50 mm depth, the first significant reduction in survival was at day 180, after the peak of the drought (p=0.031). From day 180 the next significant drop was at day 360 at the peak of the second rainy season (p=0.026) (Figure 3.3.12). This significant drop in survival during the peak of the rainy season might have been caused by the combination of two factors: First, high drought stress during the dry season would have left some plants very weak, but still surviving and second, the rapid growth from the most competitive plants when water was available would have quickly dominated lesser species. This combination might have been fatal for small and weak plants.

Survival at 100 mm depth

For the 100 mm depth the first significant decrease in survival was on day 90 (p=0.024) (Figure 3.3.12), when plants from a 100 mm depth plot succumbed to a fungal infection which targeted species with highly succulent stems like *S. allantoides* and *S. allantoides* Goldii in particular. From day 90, the next day with a significant decline in survival was day 150, during one of the most severe droughts (p=0.016). From day 150 the next significant drop in survival was on day 360, at the peak of the rainy season (p=0.020) (Figure 3.3.12). It seems that the plants that were still weak from the fungal infection were not strong enough to survive during the drought period, and the plants that survived it were still in poor health and died when water became available, due to competition from stronger plants.

Survival in the 150 mm depth

In the 150 mm depth the first significant drop in survival was not until day 180, just as in the 50 mm depth, (p=0.031) (Figure 3.3.12). After day 180 the next significant day was day 360, at the peak of the rainy season (p=0.011) (Figure 3.3.12). The greater mortality observed in the 150 mm depth occurred near the end of the experiment (Day 430). It is likely that the same plants that were able to withstand the drought at the beginning of the experiment, when young with more space and resources, were not able to withstand the high competition of the reduced space by the end of the experiment.

Plants like *S. confusum* and *S. griseum* rapidly became very big plants in the 150 mm depth substrate, in comparison with species like *S. allantoides* or *S. jurgensenii*. The higher and bigger canopy and more extended root system of these plants resulted in dominating growth within a short amount of time, and this might have contributed to the exclusion and death of less vigorous species (Figure 3.3.12). Nevertheless, not only small and slow growing plants suffered at day 300; *S. confusum* had a drop in survival too. This drop might be related to the combination of intra-competition, or competition between plants of the same species, with the dry conditions experienced at the end of the experiment in the deeper depths, especially in 150 mm (Figure 3.3.12).

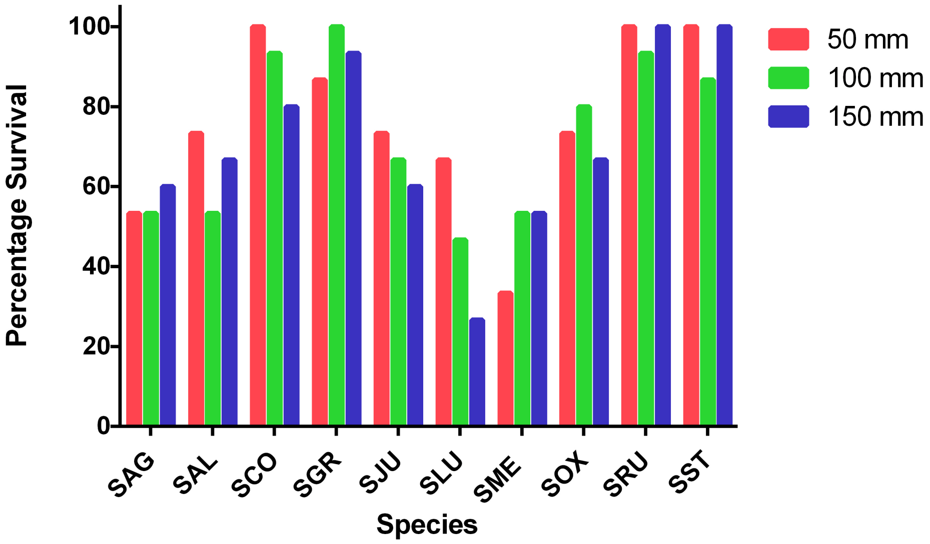


Figure 3.3.13 Final percentage survival of all species: SAG *S. allantoides* Goldii, SAL *S. allantoides,* SCO *S. confusum,* SGR *S. griseum,* SJU *S. jurgensenii,* SLU *S.* x *luteoviride,* SME *S. mexicanum,* SOX *S. oxypetalum,* SRU *S.* x *rubrotinctum* and SST *S. stahlii,* at three depths.

The results of the *Sedum* experiment suggests that the species studied can be divided into three groups in terms of their survival responses:

(1) Species with mortality rates of up to 20 percent: *S.* x *rubrotinctum, S. stahlii, S. griseum* and *Sedum confusum* (Figure 3.3.13 and Figure 3.3.14). **Strong performers**

(2) Species with mortality over 20 percent, but not more than 40 percent: *S. oxypetalum*, *S. jurgensenii, S. allantoides and S. allantoides* Goldii (Figure 3.3.13 and Figure 3.3.14). **Medium performers**

(3) Species with greater than 40 percent mortality: *S.* x *luteoviride* and *S. mexicanum* (Figure 3.3.13 and Figure 3.3.14). **Poor performers**

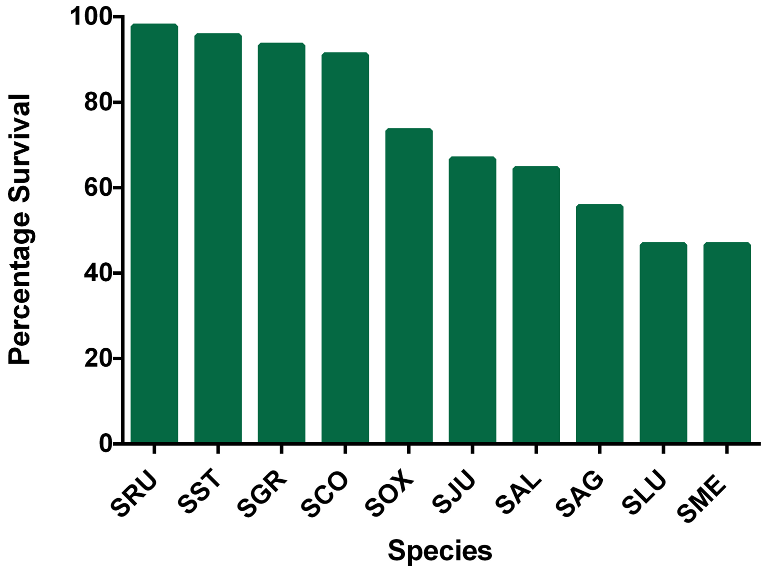


Figure 3.3.14 Final percentage survival of all species: SRU *S.* x *rubrotinctum,* SST *S. stahlii,* SGR *S. griseum,* SCO *S. confusum,* SOX *S. oxypetalum,* SJU *S. jurgensenii,* SAL *S. allantoides,* SAG *S. allantoides* Goldii, SLU *S.* x *luteoviride,* SME *S. mexicanum,* at pool eddepths.

3.3.3.2 Diameter Relative Growth Rate

The depth treatment for repeated measures of the diameter RGR differences was significant (p=0.009, Greenhouse-Geisser correction). Nevertheless it was not possible to determine between which depths the significant differences lay (Figure 3.3.15).

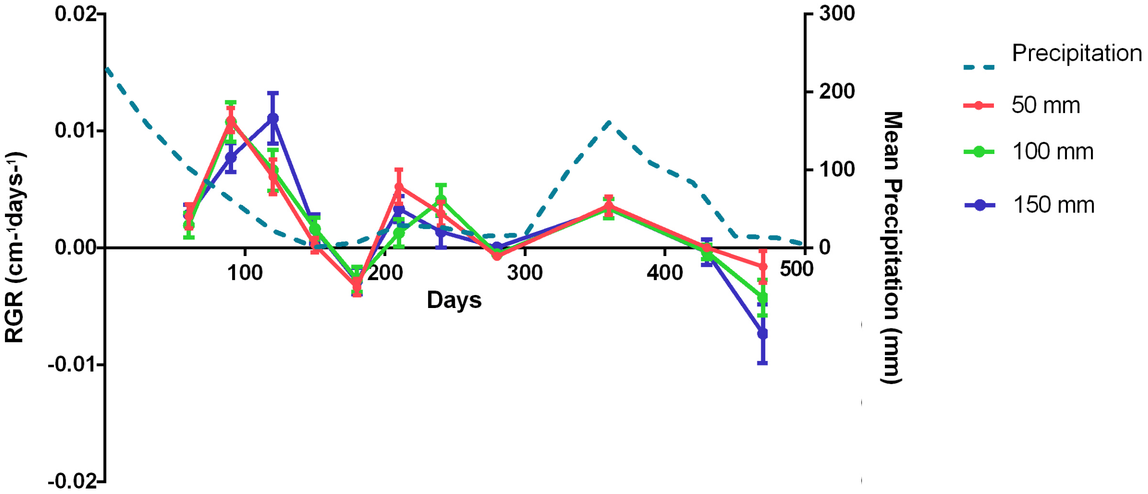


Figure 3.3.15 Diameter Relative Growth Rate for three depths and mean precipitation in mm. ±SEM bars only for between subjects. Negative RGR is due to shrinking of the species during drought.

Diameter RGR and rain distribution

The dataset of the diameters relative growth rate portrays a very similar pattern to that observed with the precipitation distribution (Figure 3.3.15). A Spearman's correlation test between the rainfall data and the diameters RGR was applied to the data, and a moderate but highly significant correlation between, the amount of rain and the relative growth rate was found (r=0.481 n=33 p=0.005) (Figure 3.3.15).

Differences in diameter RGR between species by depth

50 mm Depth.- This depth is where the most significant differences of RGR between species were found. *S. confusum*, *S. griseum* and *S. jurgensenii* had significantly higher RGR than *S. allantoides, S. mexicanum* and *S. oxypetalum* (p<0.05, Tukey HSD); *S.* x *rubrotinctum* and *S. stahlii* had significantly higher RGR than *S. allantoides* Goldii, *S. mexicanum* and *S. oxypetalum* (p<0.05, Tukey HSD); and *S.* x *luteoviride* had a significantly higher RGR than *S. allantoides* Goldii and *S. oxypetalum* (p<0.05, Tukey HSD) (Figure 3.3.16)

100 mm Depth.- The comparison of the diameter RGR between species showed that at the 100 mm depth *S. griseum* had a significantly higher RGR than *S. allantoides* Goldii, *S. allantoides*, *S.* x *luteoviride* and *S. oxypetalum* (p<0.05, Tukey HSD). *S. confusum* and *S. stahlii* had a significantly higher RGR than *S. allantoides* Goldii, *S. allantoides* and *S. oxypetalum* (p<0.05, Tukey HSD) for all cases (Figure 3.3.16).

150 mm Depth.- For this depth *S. griseum* and *S. stahlii* had a significantly higher RGR than *S.* x *luteoviride* and *S. mexicanum* (p<0.05, Tukey HSD) and *S. confusum* had a significantly higher RGR than *S.* x *luteoviride* (p=0.017, Tukey HSD) (Figure 3.3.16).

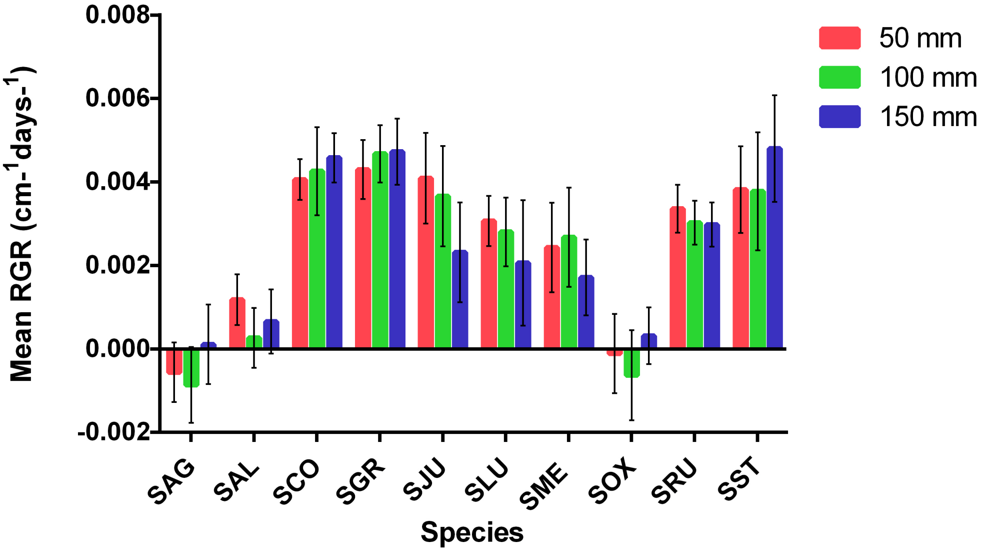


Figure 3.3.16 Mean diameter RGR for all species: SAG *S. allantoides* Goldii, SAL *S. allantoides*, SCO *S. confusum*, SGR *S. griseum*, SJU *S. jurgensenii*, SLU *S.* x *luteoviride*, SME *S. mexicanum*, SOX *S. oxypetalum*,

SRU *S.* x *rubrotinctum* and SST *S. stahlii,* between three depths, ±SEM bars. Negative RGR is due to shrinking of the species during drought or diseases.

The comparison of the mean RGR between species across all depths shows that in *S. confusum*, *S. griseum*, *S. jurgensenii*, *S.* x *rubrotinctum* and *S. stahlii* had significantly higher mean RGR, than *S. allantoides* Goldii, *S. allantoides*, *S.* x *luteoviride*, *S. mexicanum* and *S. oxypetalum* ($p<0.05$, Tukey HSD) (Figure 3.4.17).

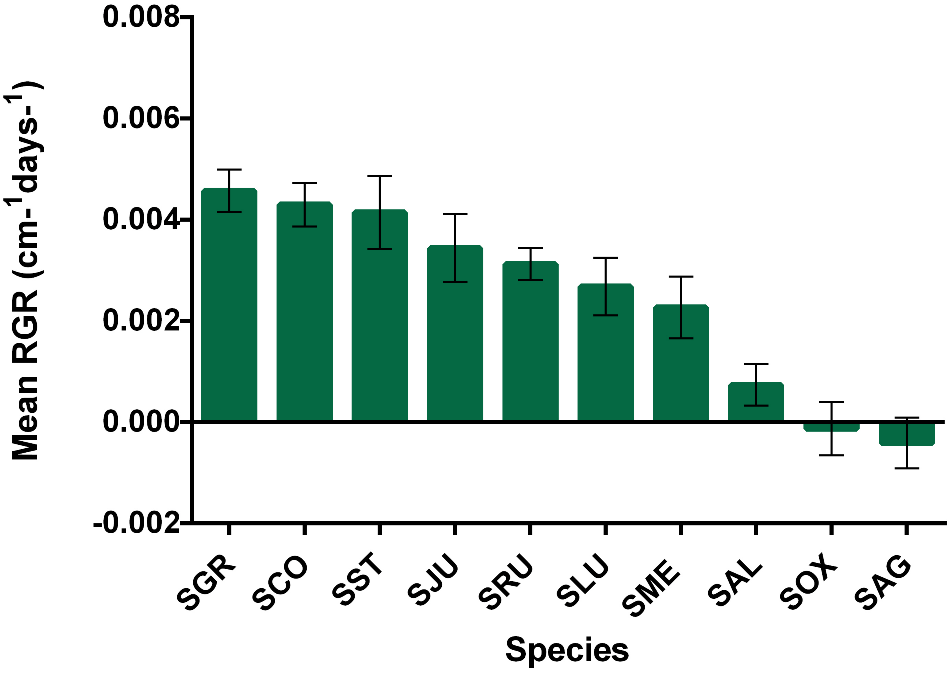


Figure 3.3.17 Mean diameter RGR for all species: SGR *S. griseum,* SCO *S. confusum,* SST *S. stahlii,* SJU *S. jurgensenii,* SRU *S.* x *rubrotinctum,* SLU *S.* x *luteoviride,* SME *S. mexicanum,* SAL *S. allantoides,* SOX *S. oxypetalum* SAG *S. allantoides* Goldii and between three depths, ±SEM bars. Negative RGR is due to shrinking of the species during drought or due to diseases.

3.3.3.3 Diameter

The repeated measures of diameters for the 10 species in the three substrate depths were significant ($p<0.001$, Greenhouse-Geisser correction). Depth significantly affected the diameter ($p=0.016$, Greenhouse-Geisser correction) (Figure 3.3.18). Differences between species were significant ($p<0.001$, Greenhouse-Geisser correction).

Differences in diameter between depths

For the overall experiment the 150 mm depth resulted in significantly greater diameters than the 50 mm depth ($p=0.018$, Tukey HSD) (Figure 3.3.18). Nevertheless, at the end of the experiment the differences of mean diameters between depths started to narrow (Figure 3.3.18). This could be explained by the increase in mortality that occurred in the 150 mm depth later on due to the high competition of big species such as *S. confusum* and *S. griseum,* in combination with the drought.

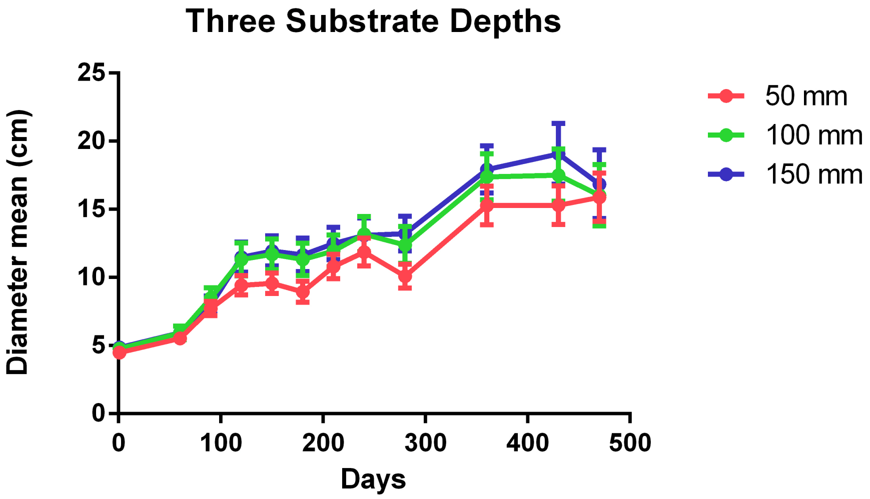


Figure 3.3.18 Diameter means for three depths and pooled sedum species. ±SEM bars only for measures between depths.

Differences between depths within species

The analysis of the mean longest and shortest diameters of the plants showed that the only species with a significant difference between depths were *S. confusum* and *S.* x *luteoviride* ($p<0.05$, Greenhouse-Geisser, correction). *S. confusum* had a significantly higher mean diameter at the 100 and 150 mm depths than at the 50 mm depth ($p<0.01$, Tukey HSD) (Figure 3.3.18), while for *S.* x *luteoviride* it was not possible to see which depth was significantly higher. The smaller sub-bushy species like *Sedum allantoides* Goldii and *S. allantoides* had a very poor performance at all depths in terms of diameter growth.

3.3.3.4 Height

Differences in height between depths

Depth had a significant effect on height ($p<0.01$, Greenhouse-Geisser correction). The comparison of the height means showed that the 150 and 100 mm depths had significantly higher means than the 50 mm depth. Although, as seen in the results by species, the differences between depths within species were too minimal to be significant by themselves, the 150 and 100 mm depths have a higher mean of height (10 mm) than the 50 mm for the whole system over time (Figure 3.3.19).

Differences in height between depths within species

Only *S.* x *luteoviride* and *S. oxypetalum* presented significant differences in height, although it was not possible to find statistically between which depths were the significant differences.

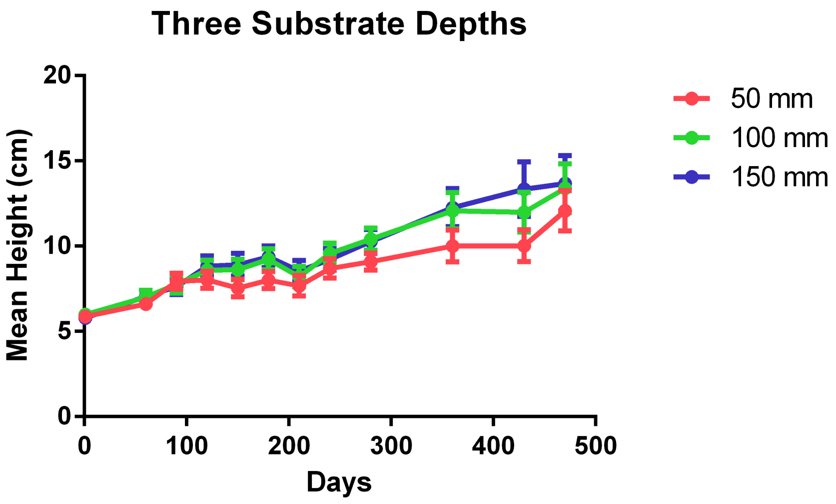


Figure 3.3.19 Height means for three depths and 10 sedum species. ±SEM bars only for measures between depths.

3.3.3.5 Percentage cover

Differences in percentage cover between depths

Depth had a significant effect on the percentage cover ($p<0.001$). Differences between species were significant ($p<0.001$) and there was a significant interaction between depth and species ($p=0.034$). The 150 mm depth had a significantly higher mean percentage cover than the 100 and 50 mm depths ($p<0.05$, Tukey HDS) (Figure 3.3.20).

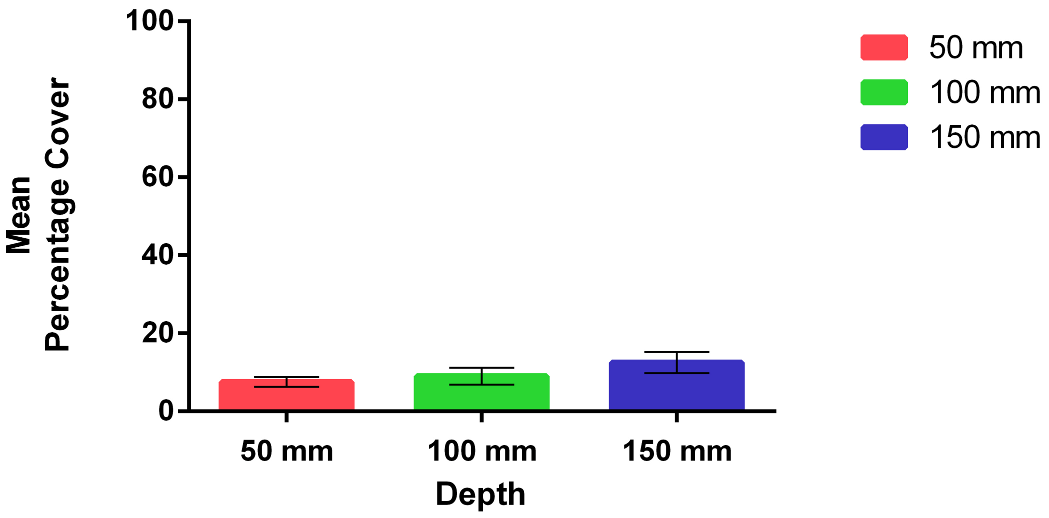


Figure 3.3.20 Mean pooled percentage cover of all ten species at three depths.

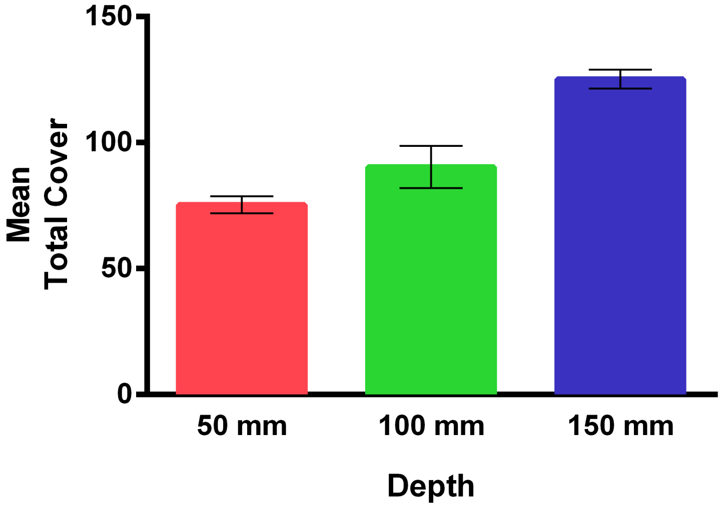


Figure 3.3.21 Total cover of all ten species at three depths.

In terms of the mean total cover for all species, the 150 mm depth was significantly higher than the 100 and 50 mm depths (Figure 3.3.21), while there was significantly more bare ground in the 50 mm depth plots, than on the 100 and 150 mm depth plots ($p<0.044$ and $p<0.003$ respectively) (Figure 3.3.22 A, B and C).

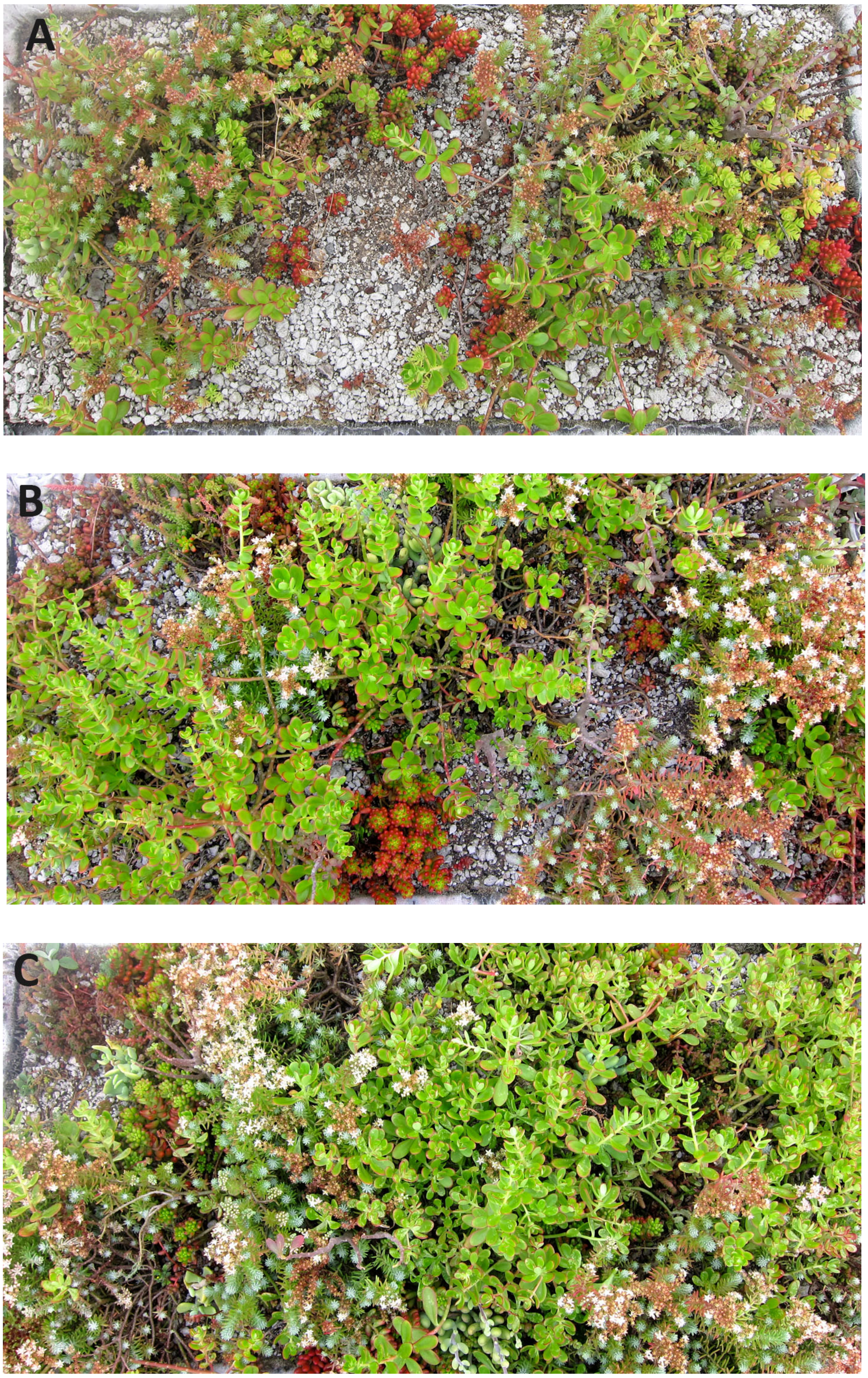


Figure 3.3.22 Final cover A) 50 mm, B) 100 mm and C) 150 mm depth plots.

Differences of cover between species

The highest overall percentage cover plants were *S. confusum* and *S. griseum* which had significantly higher percentage cover than *S. allantoides* Goldii, *S. allantoides*, *S. jurgensenii*, *S.* x *luteoviride*, *S. mexicanum*, *S. oxypetalum*, *S.* x *rubrotinctum* and *S. stahlii* ($p<0.05$) (Figure 3.3.23). This is no surprise, since these two species are the biggest of the ten species used in this experiment, and have the highest RGR as shown previously; a highly efficient combination. Nevertheless, *S.* x *rubrotinctum* had significantly higher percentage cover than *S. allantoides* Goldii, *S. mexicanum* and *S. oxypetalum* (p<0.05) and *S. stahlii* had significantly higher percentage cover than *S. allantoides* Goldii and *S. mexicanum* (p<0.05).

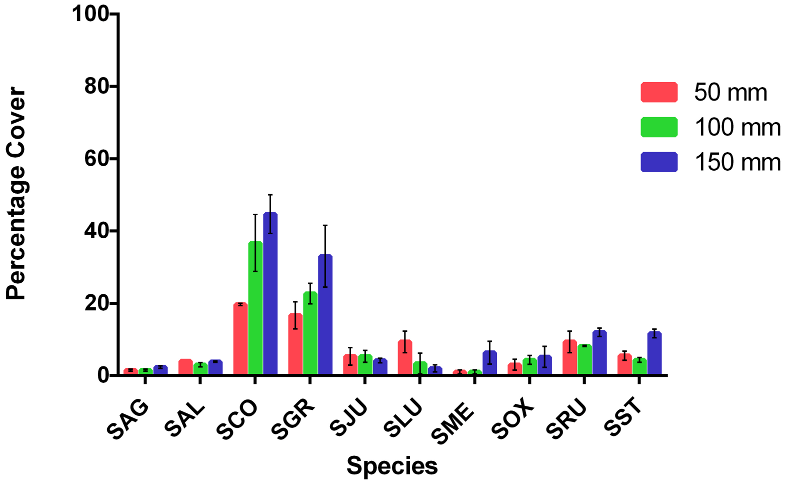


Figure 3.3.23 Mean percentage cover at three depths of ten species: SAG *S. allantoides* Goldii , SAL *S. allantoides*, SCO *S. confusum*, SGR *S. griseum*, SJU *S. jurgensenii*, SLU *S.* x *luteoviride*, SME *S. mexicanum*, SOX *S. oxypetalum*, SRU *S.* x *rubrotinctum*, SST *S. stahlii*

Differences mean percentage cover between depths within species

The comparison of means of percentage cover between depths within species showed that only two species had significant differences between depths. *Sedum confusum* at the 150 mm depth had a higher cover mean than at 50 mm depth (p=0.016, Tukey HSD) For *Sedum stahlii,* the 150 mm depth plots obtained a significantly higher mean percentage cover compared to the 100 mm and the 50 mm depths (p<0.01, Tukey HSD).

3.3.3.6 Dry weight

The biomass of the plants growing in the three depths showed no significant differences between treatments (p=0.099), while the differences between species were highly significant (p<0.001). The interaction between depth and species was significant (p=0.0314), which means that the differences in depths responses are related directly to species differences (Figure 3.3.24).

It is surprising not to see significant differences in the dry weight dataset, considering the differences found in diameter RGR, diameter; height and percentage cover for the pool data. This lack of difference might be explained in different ways. The first explanation concerns the differences in growth between *S. confusum* and *S. griseum* (Figure 3.3.25). These two species become highly dominant at the 100 and 150 mm depths. This factor could have deprived smaller species of space and resources, which made it impossible for them to grow in these deep substrates. Another possible explanation is that only the big species are affected by depth of substrate and that smaller species may behave the same way given any depth. Nevertheless, as we see with the diameter RGR, the differences between depths were significant.

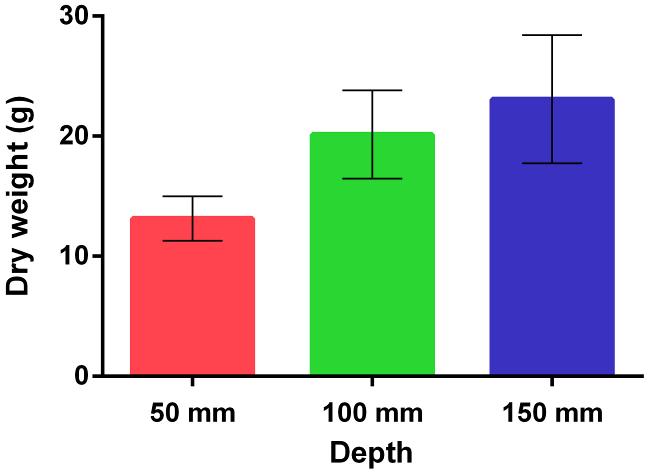


Figure 3.3.24 Mean total dry weight of pooled species at three depths, ±SEM bars.

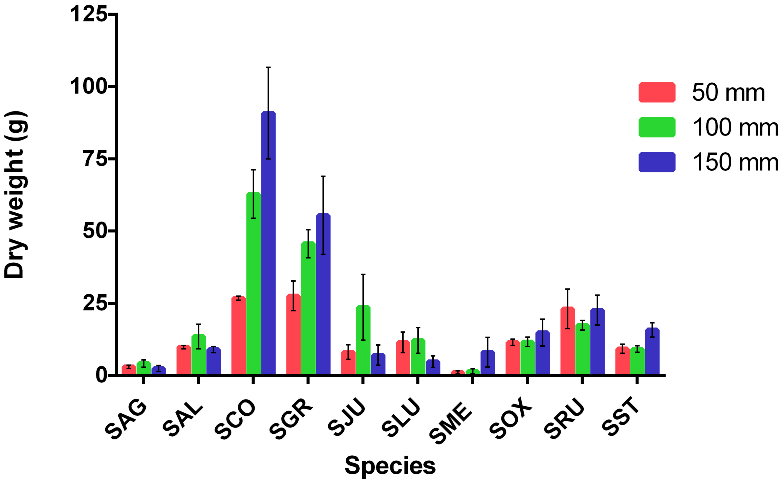


Figure 3.3.25 Mean dry weight for SAG *S. allantoides* Goldii, SAL *S. allantoides,* SCO *S. confusum,* SGR *S. griseum,* SJU *S. jurgensenii,* SLU *S.* x *luteoviride,* SME *S. mexicanum,* SOX *S. oxypetalum,* SRU *S.* x *rubrotinctum* and SST *S. stahlii,* between three depths, ±SEM bars.

3.3.3.7 Flowers

Individual *Sedum* flowers are very inconspicuous. Nonetheless, when a high number of plants are growing they can provide a multitude of inflorescences and add vibrant colour to the roof. The flowering data for this experiment does not count the amount of flowers per plant, only the percentage of plants in flower at any one time. The flowering periods of the ten *Sedum* species (Figure 3.3.26 and Figure 3.3.27) show that several species flower at two peak seasons across the year. For some, the first period is during the beginning of summer, from June to August, and the next peak flowering time is during the winter from December to January.

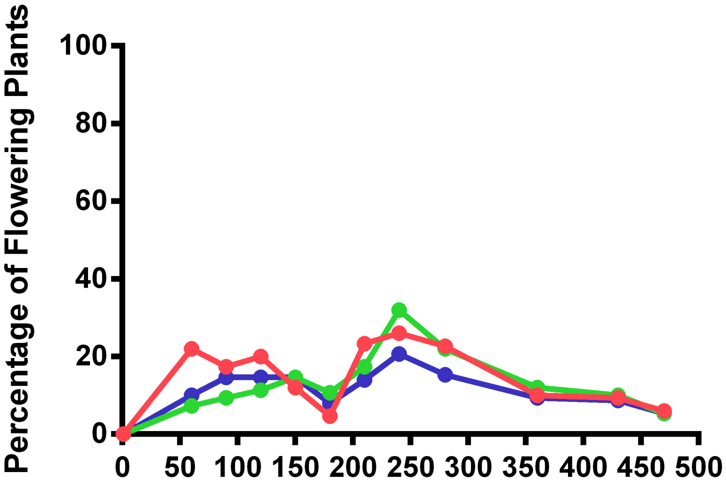
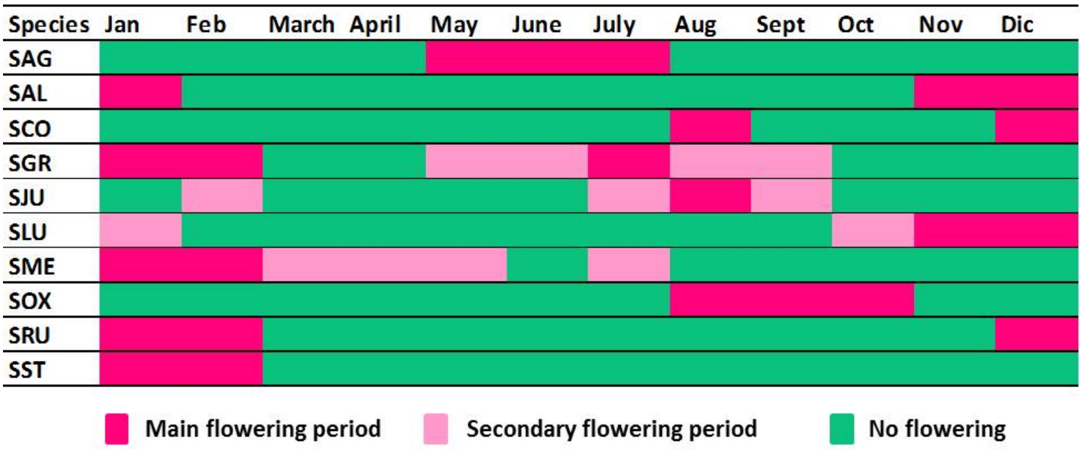


Figure 3.3.26 Repeated measures of mean percentage of flowering plants per depth



Species	Jan	Feb	March	April	May	June	July	Aug	Sept	Oct	Nov	Dic
SAG	🟩	🟩	🟩	🟩	🟥	🟥	🟥	🟩	🟩	🟩	🟩	🟩
SAL	🟥	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟥	🟥
SCO	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟥	🟩	🟩	🟩	🟥
SGR	🟥	🟥	🟩	🟩	▨	▨	🟥	▨	▨	🟩	🟩	🟩
SJU	🟩	▨	🟩	🟩	🟩	🟩	▨	🟥	▨	🟩	🟩	🟩
SLU	▨	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	▨	🟥	🟥
SME	🟥	🟥	▨	▨	▨	🟩	▨	🟩	🟩	🟩	🟩	🟩
SOX	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟥	🟥	🟥	🟩	🟩
SRU	🟥	🟥	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟥
SST	🟥	🟥	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩

🟥 Main flowering period ▨ Secondary flowering period 🟩 No flowering

Figure 3.3.27 Phenology for SAG *S. allantoides* Goldii, SAL *S. allantoides,* SCO *S. confusum,* SGR *S. griseum,* SJU *S. jurgensenii,* SLU *S.* x *luteoviride,* SME *S. mexicanum,* SOX *S. oxypetalum,* SRU *S.* x *rubrotinctum* and SST *S. stahlii.*

The phenological rhythms of succulent species in arid places are tied to several factors such as: water availability, the light and temperature periods. In perennial succulents the flowering period can coincide with the vegetative growth and/or precede it or follow it. Some succulents can flower only in particular and limited periods of time, while other species do it in response to climatic conditions, and therefore can flower at any time and even more than once a year. Perennial succulents have different strategies to attract pollinators. Energy can be invested in only a few big and attractive flowers, like in cacti, or invested in complex inflorescences with dense amount of small flowers, like in the *Sedums*. In both cases, a population can either synchronize all plants to flower during a limited period, or present flowering sequences for a longer period (Willert 1992).

Differences of percentage of flowering plants between depth

Depth of substrate significantly affected the percentage of flowering plants (p=0.019, Greenhouse-Geisser correction), nevertheless it was not possible to know which depth was significantly different from the other based on the model. The depth with the highest percentage of flowering plants was the 50 mm depth, with a mean of 14.44 % during the whole time of the experiment, and the depth with the least percentage of flowers was the 150 mm with 11.27%, (Figure 3.3.26). Within species there were no significant differences between depths. The high number of flowering individuals in the 50 mm depth compared to the 150 mm depth may be attributed to the possible greater stress experienced. With less favouring conditions the plants may turn to sexual reproduction, whereas with more resources put the energies into vegetative growth.

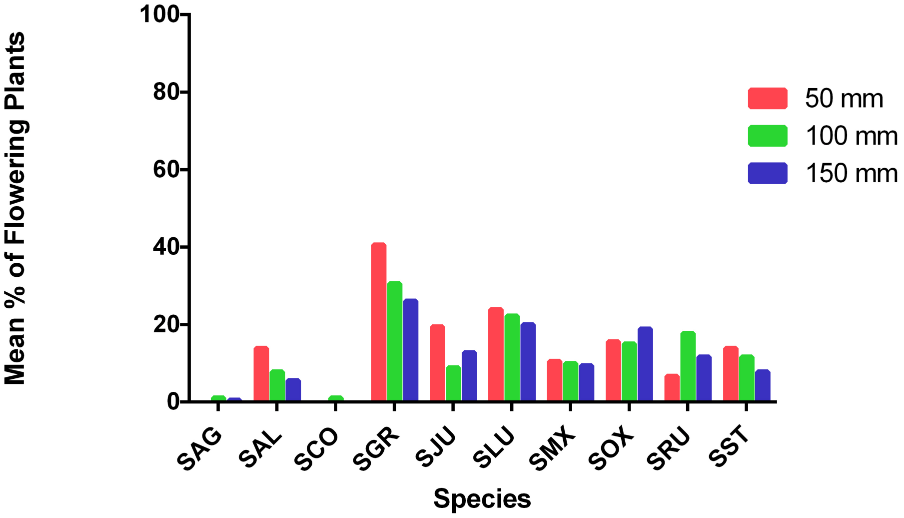


Figure 3.3.28 Percentage of flowering plants per species at three depths. SAG *S. allantoides* Goldii, SAL *S. allantoides,* SCO *S. confusum,* SGR *S. griseum,* SJU *S. jurgensenii,* SLU *S.* x *luteoviride,* SME *S. mexicanum,* SOX *S. oxypetalum,* SRU *S.* x *rubrotinctum* and SST *S. stahlii.*

Sedum griseum, had a significantly higher number of plants flowering than any of the other species (p<0.05, Tukey HSD). *Sedum* x *luteoviride,* also had a high number of flowering plants, significantly higher than that *S. jurgensenii*, *S.* x *rubrotinctum*, *S. stahlii*, *S. mexicanum*, *S. allantoides*, *S. allantoides* Goldii and *S. confusum* (p<0.05, Tukey HSD). The species with less significant number of flowering plants were *S. allantoides* Goldii, and *S. confusum* (p<0.05, Tukey HSD) (Figure 3.3.28).

3.4 Discussion and conclusions

This section will present the combined conclusions for the two planting seasons experiment, as well as the conclusions pertaining to the extended planting season of the same experiment, in answer to the questions raised in the introduction to this chapter.

3.4.1 Which is the optimal planting season for the establishment of Mexican Sedum species in the Cwb climate?

As presented in the previous sections, survival, diameters and heights were significantly greater in plants established during the rainy season. Nevertheless, the diameters data showed, how the gap between the two seasons started to close at two moments: first, when rains became available to the dry season established plots around day 120, and the next at day 240 when plants established in the wet season experienced a mean precipitation of 5 mm. The reduction of diameter of the wet season established plants can be a response to various factors, such as dehydration, since in the extended experiment of the wet season plant it was evident that fluctuations diameter (as the Spearmans's correlation or the diameter RGR showed) were in synchrony with seasonal water availability. Nevertheless, the fact that in the wet planting season plants were able to increase their diameter growth faster than the dry season plants, implies that the total cover of the roof might be achieved faster if roofs are set out for wet season planting. This feature is desirable to avoid the establishment of invasive weeds in the system. Furthermore, if supplemented watering is not possible, establishing the new green roof in the wet season is a requisite for success.

3.4.2 Which is the optimal substrate depth to the growth of Mexican *Sedum* species in the Cwb climate in terms of plant performance?

The results for the depths showed that for both seasons, diameter and height were significantly greater for plants grown in the 100 and 150 mm depth than in the 50 mm depths. While for survival only, the 150 mm depth was higher than the 50 m depth. This was probably due to the fungal infection which several plants were prone to in some plots of the 100 mm depth. The diameter RGR did not present any significant change for the overall experiment.

The tendency for having significantly lower growth rates at the 50 mm depth was exacerbated by the dry planting season. Survival, diameter, height, and RGR were higher at the 100 mm and 150 mm depths, than at the 50 mm depth, but no differences were found between the two deeper substrates. The mean cover % of all species per depth for the wet season established plants presented a significantly higher mean for the 150 mm depth in comparison with the 100 and 50 mm depths. Here, again, the fungal problem at the 100 mm depth might have played a role to subsequent lower cover %. Taking in to consideration the above elements, the increase in substrate depth provides greater water storage in the substrate which the roots can access. For this reason alone, a minimal substrate depth should be avoided if at all possible, for optimal survival of Mexican plants in the dry season.

The comparison between the short and the extended wet season data showed the same results in terms of survival, with no differences between depths. The diameter changed from having the 150 and 100 mm depths significantly higher than the 50 mm depth, to only the 150 mm depth being significantly higher than the 50 mm depth. Nevertheless, in terms of height the opposite occurred and from having only in the 100 mm depth taller plants than the 50 mm, both deeper substrates attained taller plants than the 50 mm. This suggest that in the extended experiment, plants of the 100 mm depth were not able to grow much more horizontally and instead had to grow taller to compete for light and space. For the percentage of plants flowering, in the extended wet season experiment it is impossible to know which depth provide significantly greater flowering but the 50 mm depth had the highest percentage of flowering plants overall.

It is known that heterogeneous substrate depths are desirable for the improvement of biodiversity on roofs (Brenneisen, 2003). Therefore rather than focusing on the best depth for all species, it maybe better to know which species grow better at each depth and obtain information concerning how to develop different soil and vegetation structures on the roof. Following these criteria, species like *S. confusum* are better for 100 and 150 mm depths, and species like *S. jurgensenii* are more suitable in 50 mm depth, while other species like *S. griseum* and *S.* x *rubrotinctum* can be used at any depth. Nevertheless, if it is necessary to determine a standard minimum depth for targeted Crassulaceae species for Cwb climates, a 100 mm depth achieves significantly less bare surface ground than the 50 mm depth, holds back, to some extent, the aggressive growth of big vigorous species, and thereby allows small and lower growing species to develop more. This leads to a higher diversity on the roof. Nevertheless, this is seen only with the Crassulaceae species of this present study, and for other type of plants, further research needs to be done.

3.4.3 Which of the ten selected Mexican *Sedum* species have the best performance on green roofs in the Cwb climate?

According to survival for the wet season established plants the 10 plant species can be separated into three groups: **Group 1**) Species with survival of 80 % or more (*S. confusum, S. griseum, S. stahlii*, *S.* x *rubrotinctum*) **Group 2**) Species with a survival between 40 % and 80% (*S. oxypetalum*, *S. jurgensenii, S. allantoides* and *S. allantoides* Goldii,) and **Group 3**) Species with less than 60 % survival (*S.* x *luteoviride* and *S. mexicanum*). This criteria can therefore be used to inform future plant selection criteria for Mexican green roof projects

Group 1

Group 1 is formed by *S. confusum*, *S. griseum*, *S. stahlii* and *S.* x *rubrotinctum* which had the higher survival and is formed with the most vigorous plant species of the experiment. The species that work better in all depths regardless of the planting seasons were *S. griseum* and *S.* x *rubrotinctum.* These two species show a healthy habit and constant growth, even in the shallow substrates and even when planted during the dry season. *S. griseum* is a species that is widely distributed in the Mexican Transverse Neo-volcanic Belt and some populations are found in the Mexican Plateau (Clausen, 1959). It is a woody plant with low succulence in comparison with other species, but its drought tolerance might be due to its habit of growing on cliffs or on lava rocks exposed to the direct sun during the day (Clausen, 1959). *S.* x *rubrotinctum's* extreme tolerance to drought maybe attributed to its hybrid vigour from its parents *Sedum pachyphyllum* and *Sedum stahlii,* both of which are highly drought tolerant species. *S. stahlii* had a good performance in most of the depths in both seasons, with the exception of the 50 mm depth in the dry season where it had a low survival and performed poorly in most parameters. This species' stem is thin and woody, and it probably requires high quantities of water in order to produce substantial roots. At 150 mm depth its leaves were able to root successfully and form more plantlets. Nevertheless, this species does not have many appreciable aesthetic qualities and can become leggy by losing lower leaves.

S. confusum showed a very aggressive growth during the wet season and in the deeper substrates when planted in the dry. It grows tall and spreads rapidly if water is available during the establishment period. Once mature under these conditions it can withstand drought, but it is a species that should be used in a minimum of 100 mm depth substrate. During the experiments the plants produced very low amount of flowers, and it would be interesting to see if over a longer time period it produces more.

Group 2

This group is formed by species that had less than 80 % survival but more than 40%. *S. allantoides* and *S. allantoides* Goldii showed a better survival during the wet season, nevertheless these are species that are prone to fungal infections at the rooting stage, so it is advisable to plant them with a root stock or apply a fungicide before planting. These species are very slow growing and, even though their survival was higher when established in the wet season, their performance was better when planted during the dry season. As mentioned before, these plants grow on rocks with very low competition and, in less competitive areas, they can grow at a steady rate and expand horizontally. They have highly aesthetic qualities and the flowers are visited by bees. It these species are going to be use in green roofs in Cwb climates the planting in a slightly higher density than other species would be advisable.

S. oxypetalum and *S. jurgensenii* are both species native to the Pedregal de San Angel, in Mexico City were the experiment was set up. Just for this reason their survival on the roof and good growth is an advantage since the species are losing their habitat by the pressure of the city on the reserve. *S. oxypetalum* grows like a small tree therefore it can be used as an accent element on the roof and its' flowers attract bees. Both species have to be planted during the wet season or with a rootstock during the dry to have a good establishment.

Group 3

S. mexicanum had the worst performance of all the species studied. Most of the plant died back during the dry season, with only a small portion of the plant alive, and growing back during the rains. Therefore the use of this species is advisable only for highly irrigated roofs during the dry season or for semi-shaded areas. *S.* x *luteoviride* showed a better survival when planted during the wet season, and better performance at the beginning of the experiments in the 100 and 150 mm depth. Nevertheless, the plant was not able to cope with the competition of bigger plants in the 150 mm depth. Therefore, this species would be most appropriately used with other slow growing species like *S. allantoides* and *S. allantoides* Goldii or planted with very low densities of more vigorous species.

3.4.4 Final recommendations and future research

The result of this experiment strongly support the use of a substrate depth of at least a 100 mm depth on Cwb climates when incorporating Crassulaceae species but, in order to improve biodiversity, variability in depths should be the aim for all roofs (Brenneisen, 2003, Gedge et al., 2010, Kadas, 2006). It appears to be the most preferable to plan the planting of the roof just days before the onset of the rainy season in order to achieve a high survival and the most rapid cover. If possible, cuttings should be treated before planting with a fungicide, but if that is not possible, then one should avoid using very succulent cuttings of species such as *S. allantoides* or attempt to plant them in plugs to avoid infections after establishment.

The hottest period in the Cwb climate occurs during the spring, when very few rains events occur. For this reason therefore, research of the cooling effects of plants on buildings has to consider more the reflection properties of the plants than the transpiration properties of the species, unless the roofs can be watered frequently during this stage, an option that is not suitable for cities like Mexico City. Nevertheless, during the wet season high precipitation events have to be managed in the cities and high transpiration rates for plants on the roof is preferably and perhaps required. Therefore, plants with a water use plasticity, able to withstand drought and heat, as well as high amounts of precipitation and able to attain and maximise high transpiration rates (such as species from granite outcrops target by Farrell et al. (2013) in Australia) are needed.

Future research of plant selection should be done in parallel with surveys of the fauna visiting and/or living on the roof, during the trials, to achieve a broader knowledge about the relationships and benefits of the plants with the surrounding environment and factor it is as important as the other parameters for the plant selection.

Chapter 4 Screening selected species from four Crassulaceae genera for Cwb climate

4.1 Introduction

After the two-planting-seasons experiment comparing plant performance between three substrate depths, the results strongly suggested that the optimal planting season for successful establishment in the Cwb climate is during or just prior to the summer, and the minimum substrate depth for good plant performance is 100 mm. Taking these parameters into consideration, a plant screening was set up to investigate the performance of different species of four different genera of the Crassulaceae family, identified as suitable candidates using from the Köppen-Geiger-derived plant selection methodology.

The introduction of a higher number of new species into the green roof plant palette for the Cwb climate can help improve the colour, texture and flowering composition of the green roofs. In the particular case of Mexico City, this is important since the green roofs of the city are dominated by only three *Sedum* species, *S. griseum, S. dendroideum* ssp. *praealtum*, and *S. moranense.* Although it is important to also integrate a wider variety of different plant forms, such as grasses, geophytes and forbs, testing other species of the diverse Crassulaceae family native to Mexico is a useful starting point. This is because the Crassulaceae family is important in terms of native biodiversity in Mexico and the habitats of its species are being destroyed by urbanization, with many species being displaced. Secondly, the successful Crassulaceae species from the screening can further be utilised as specific climatic and vegetation zone indicators and can henceforth inform the future search for new green roof species from a wider variety of plant forms.

The species tested in the screening are from the *Echeveria, Graptopetalum, Pachyphytum* and *Sedum* genera, which (as previously shown in Chapter 2.4) contain many of the most suitable potential species for Cwb climate, with relatively rapid growth rates and larger plant size. Genera such as *Dudleya* were not included for this screening, due to the higher rain distribution during winter in their native habitat, and species from the *Villadia* genus were also excluded as they are usually very small and slow growing.

4.2 Methods and materials

A screening experiment was set up to compare the performance of 17 Crassulaceae species from 4 genera: ***Echeveria***, ***Graptopetalum***, ***Pachyphytum*** and ***Sedum*** (Table 3.4.1). The species native ranges including from the Mexican Transverse Neovolcanic Belt, the Sierra Madre Occidental, the Sierra Madre Oriental, the Sierra Madre de Oaxaca, and the Mexican Plateau. As described in Chapter 2, a more extensive and comprehensive list of potential candidate species was created for Cwb climate, but due to plant availability, aesthetics, and intractable or unsuitable growth forms 17 species were chosen for further screening and thorough investigation.

During the third week of July 2012 the screening was set up on the roof of one of the buildings of the Institute of Biology of the National Autonomous University of Mexico (IBUNAM). The plots were North facing, under full and direct sun with no shading from any tree or any adjacent buildings. The screening consisted of triplicated plots of 5 individual rooted cuttings of 17 species allocated in 1.20m x 1.20m x 10 mm height plant beds. Each plot was constructed with wooden frames formed of 20 mm planks of 1.22 m length and 125 mm in height, in order to hold 100 mm deep substrate plus a 20 mm thick drainage layer and 5 mm for filter sheets and a root barrier. The frames were placed on top of a root membrane sheet that was used to protect the waterproof membrane and the roof surface bellow. Inside each frame the layers of the system were formed by a 2 mm anti-root membrane sheet, a 1 mm protective sheet, a 20 mm drainage layer composed of dust free white volcanic rock, a 1 mm filter layer and 100 mm depth of substrate. The root barriers, protective sheet and filter layer were supplied by *Geoproductos de México*. Each anti-root membrane positioned inside the frame had 6 drainage orifices of 25 mm in diameter disposed in equidistance on each side of the frame with a total of 24 drainage holes per plot. Since the wooden planks would not sit perfectly level on the floor of the roof and there were several gaps between the boards and the floor, no extra holes were required for drainage on the wooden boards (Figure 4.2.1 A).

Each bed was filled with 100 mm depth of substrate and no shading was projected from the bed frames for the plants (Figure 4.2.1 B). The substrate was composed of 60% pumice rock and 40% of garden waste compost, both elements sieved on a 10 mm grid and thoroughly mixed at the Botanic Garden of the IBUNAM. The pumice was bought from suppliers *Jardines Flotantes* in the Xochimilco Delegation in Mexico City and the compost was kindly donated by the composting facility of the National Polytechnic Institute campus Mexico City.

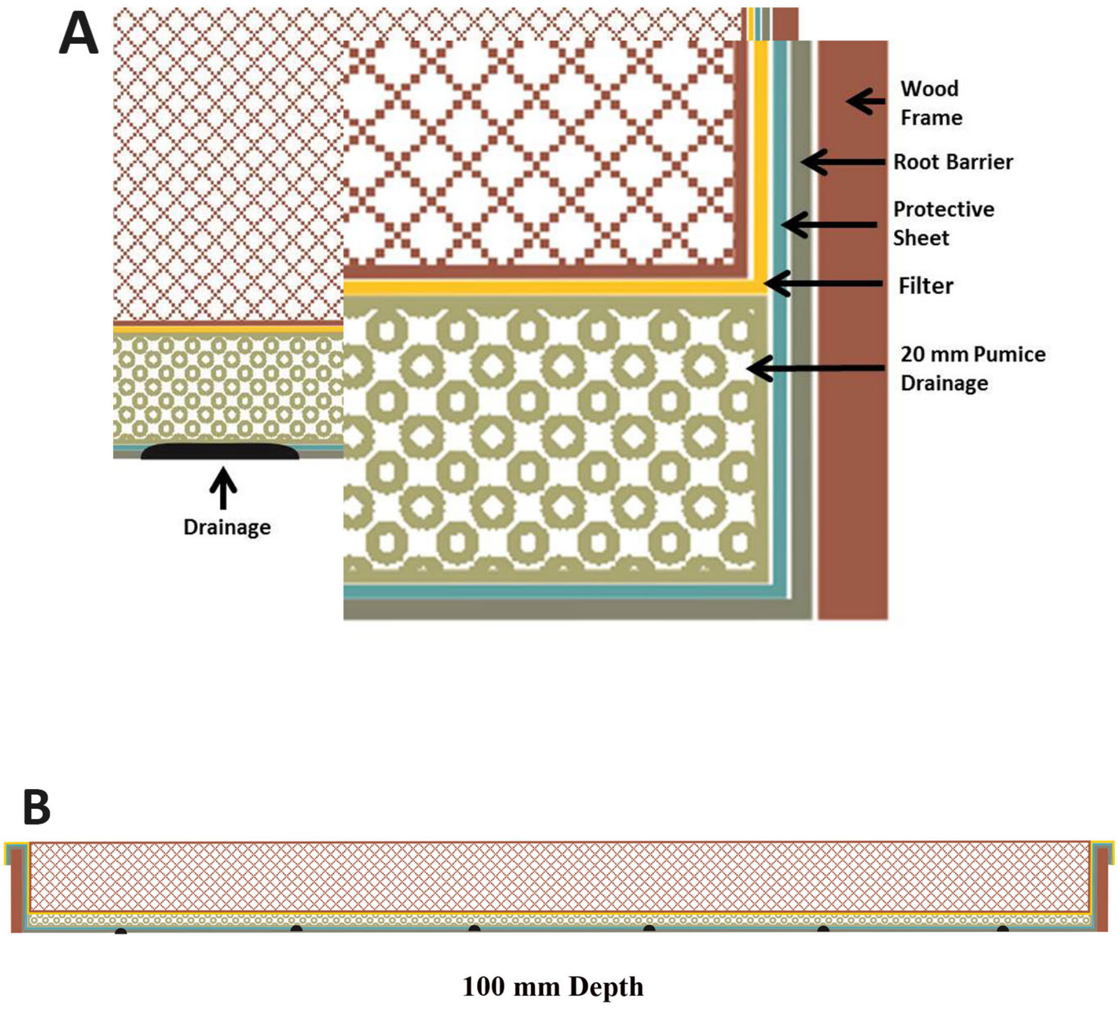


Figure 4.2.1 A) Detail of experiment grow units with layers. B) Sample of experimental unit.

Five rooted plants of each of the seventeen species were planted at random, with a total of 102 plants per plot. Plants were planted in a 100 x 100 mm grid. All plants had a minimum diameter of 30 mm and a maximum diameter of 40 mm. Rosette height was a minimum of 35 mm and a maximum of 40 mm. Subshrub plants had a minimum height of 130 mm and maximum 135 mm. All plants were propagated at and donated by the installations of the National Crassulaceae Collection at the Botanic Garden of the IBUNAM. All plants were gradually acclimatized from the shaded greenhouse to full sun over the case of two weeks prior to the initiation of the screening experiment. Plants were planted in July 2013 in the first third of the rainy season; for this reason plants were not watered during their establishment. After establishment; and after the onset of the dry season plants were given supplemental water by being watered until water started to leak from the plots. This supplemented water was given only on two date: Day 180 (November) and Day 240 (January), due to the severe drought.

4.3 Selected species

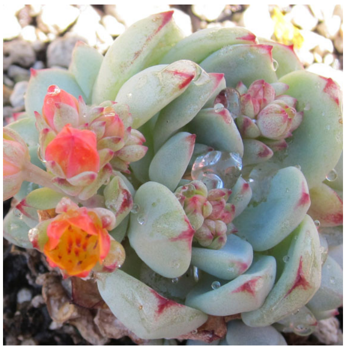
Using the plant selection methodology developed and detailed in Chapter 2. Crassulaceae species were identified from the key Mexican physiographic zones. Of the 17 Crassulaceae species used (Table 4.3.1) 5 are native to the Mexican Transverse Volcanic Belt: *E. coccinea* (Cavanilles) De Candolle (Figure 4.3.1 B), *E. elegans* Rose (Figure 4.3.1 D), *E. prolifica* Moran & Meyran, Rose (Figure 4.3.1 G), *Graptopetalum superbum* Acevedo-Rosas (Figure 4.3.1 K) and *Sedum hernandezii* Meyrán (Figure 4.3.1 O). Two species, *E. pringley* ssp. *parva* Kimnach (Figure 4.3.1 F) and *E. shaviana* Walther (Figure 4.3.1 I), are native to the Sierra Madre Occidental. Three species are from the Sierra Madre Oriental: *Graptopetalum paraguayense* ssp. *paraguayense* (Figure 4.3.1 J), *Pachyphytum werdermannii* von Poellnitz (Figure 4.3.1 N), and *S. palmeri* ssp. *emarginatum* Watson (Figure 4.1.19 Q). Three species were chosen from the Sierra Northern Mountains of the Sierra Madre de Oaxaca: *E. derenbergii* Purpus (Figure 4.3.1 C), *E. gigantea* Rose & Purpus (Figure 4.3.1 E), *E. pulvinata* (Figure 4.3.1 H) and *S. pachyphyllum* Rose (Figure 4.3.1 P). Three species, *E. agavoides* Lenaire (Figure 4.3.1 A), *P. hookeri* (Salm-Dyck) Berger (Figure 4.3.1 M) and *P. fittkaui* Moran (Figure 4.3.1 L), are from the Mexican Plateau.

Species	Plant Form	Height	Foliage colour	Flower colour	P. zone	Altitude range	Vegetation Type
Echeveria agavoides	Rosette	3 to 8 cm	Dark or bright green	Orange to yellow	MP	Approx 2400 m	Natural Grassland
Echeveria coccinea	Shrubby	25 to 30 cm	Greyish green	Red	TVB	2500 m	Xerophilous scrub
Echeveria derenbergii	Rosette	5 to 6 cm	Glaucous green	Yellow	NMSO	1800 m	Deciduous tropical forest
Echeveria elegans	Rosette	3 to 7 cm	White to pale greenish	Pink and yellow	TVB	Approx 2500 m	*Pinus-Quercus* forest
Echeveria gigantea	Rosette	18 to 20 cm	Pale blue_green	Pink	NMSO	2130 m	Deciduous tropical forest
Echeveria pringley var. *parva*	Shrubby	30 to 40 cm	Bright green	Orange	MP	1305 m	Deciduous tropical forest */Pinus-Quercus* forest
Echeveria prolifica	Rosette	3 to 5 cm	Glaucouse-green	Yellow	TVB	No data	*Pinus-Quercus* forest
Echeveria pulvinata	Shrubby	10 cm or more	Green pubescent	Scarlet red	NMSO	Approx 900 m	Deciduous tropical forest / *Pinus-Quercus* forest
Echeveria shaviana	Rosette	3 to 5	Glaucouse-green	Rose	SMO	1800 m	*Pinus-Quercus* forest
Graptopetalum paraguayense ssp. *paraguayense*	Rosette	20 to 30 cm	Glaucouse pink	White	SMO	No data	No data
Graptopetalum superbum	Rosette	20 to 30 cm	Glaucouse violet	Yellowish	SMOC	410 m	Deciduous tropical forest
Pachyphytum fittkaui	Rosette	30 to 40 cm	Green bright	Pink	MP	1200 to 2100 m	Grassland
Pachyphytum hookeri	Rosette	10 cm	Glaucouse greyish	Bright pink	SMOC	2500 Approx	*Pinus-Quercus* forest
Pachyphytum werdermannii	Rosette	10 cm	Glaucouse greyish-piknish	Pale pink to bright pink	SMO	700 m	Woody Xerophilous scrub -piedmont
Sedum hernandezii	Subshrub	14 cm	Bright green	Yellow	TVB	2400-2500 m	*Quercus-Pinus* forest
Sedum pachyphyllum	Subshrub	25 to 50 cm	Glaucouse light green	Yellow	SMNO	1800-2100 m	Deciduous tropical forest
Sedum palmeri	Subshrub	15 to 20 cm	Light green	Yellow	SMO	1600 m	Succulent. Xerophilous scrub (rossette)

Table 4.3.1 Crassulaceae species used in the screening information based in (Clausen, 1959, Etter and Kristen, 1997, Evans, 1983, INEGI, 2011a, Pilbeam, 2008, Praeger, 1921, Stephenson, 1994, Reyes-Santiago et al., 2004). Physiographic zones key: TVB-Transverse Volcanic Belt, SMO-Sierra Madre Oriental, SMOC-Sierra Madre Occidental, NMO-Northern Mountain System of Oaxaca, MP Mexican Plateau. *Non data* on the altitude or vegetation type columns means it was not found of records in literature and first descriptions of the plant species.

A) *Echeveria agavoides*

B) *Echeveria coccinea*

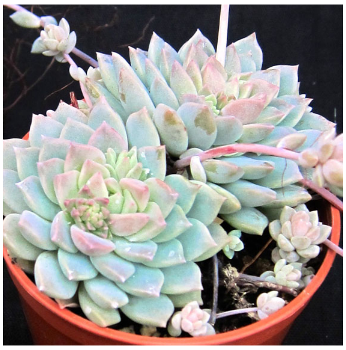


C) *Echeveria derenbergii*

D) *Echeveria elegans*

E) *Echeveria gigantea*

F) *Echeveria pringley* var. *parva*

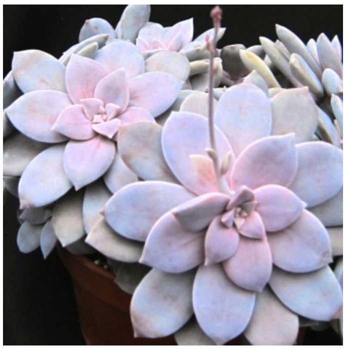


G) *Echeveria prolifica*

H) *Echeveria pulvinata*

I) *Echeveria shaviana*

J) *Graptopetalum paraguayense* ssp. *paraguayense*



K) *Graptopetalum superbum*

L) *Pachyphytum fittkaui*

M) *Pachyphytum hookeri* **N)** *Pachyphytum werdermannii* **O)** *Sedum hernandezii*

P) *Sedum pachyphyllum* **Q)** *Sedum palmeri* ssp. *emarginatum*

Figure 4.3.1 Representative images of selected species for the Mexico City screening A) *Echeveria agavoides,* B*)* *Echeveria coccinea*, C) *Echeveria derenbergii,* D) *Echeveria elegans,* E) *Echeveria gigantea,* F) *Echeveria pringley* var. *parva,* G) *Echeveria prolifica,* H) *Echeveria pulvinata* I) *Echeveria shaviana,* J) *Graptopetalum paraguayense* ssp. *Paraguayense,* K) *Graptopetalum superbum,* L) *Pachyphytum fittkaui,* M) *Pachyphytum hookeri* N) *Pachyphytum werdermannii,* O) *Sedum hernandezii,* P) *Sedum pachyphyllum,* Q) *Sedum palmeri* ssp. *emarginatum*

4.4 Results and discussion

4.4.1 Temperature and precipitation

To begin analysing the growth and survival responses of the species in the Mexico City green roof screening it is necessary to put the experiment into the context of the prevailing seasonal changes in temperature and precipitation experienced by the plants.

The screening lasted 17 months, during which time the mean precipitation was 59.7 mm and the total accumulated precipitation was 1075.7 mm (Figure 4.4.1 A). The period with the lowest precipitation in 2011 was during December (Day 150) with only 0.9 mm and, in 2012, during October 2012 with 12.7 mm (Day 480) (Figure 4.4.1 A). The instance with highest precipitation for 2011 was during the summer months of July and August (Day 1 to 45) with 230.5 and 158.9 mm respectively. For 2012 the highest precipitation also occurred during July and August (Days 360 to 390) with 160.5 and 108.4 mm respectively (Figure 4.4.1 A). Over the course of the screening, the mean temperature was 17.0 °C, the mean maximum temperature was 23.6 °C, and the mean minimum temperature was 10.6 °C. The instances with the highest mean maximum temperatures were in August 2011 (Day 40) with a reading of 24.5 °C and in May 2012 (Day 300) with a reading of 27 °C (Figure 4.4.1 B). The lowest mean minimum temperatures in 2011 were during December (Day 150) with a mean of 6.3 °C and, in 2012, during November (Day 470) with a mean of 12.7 °C (Figure 4.4.1 B).

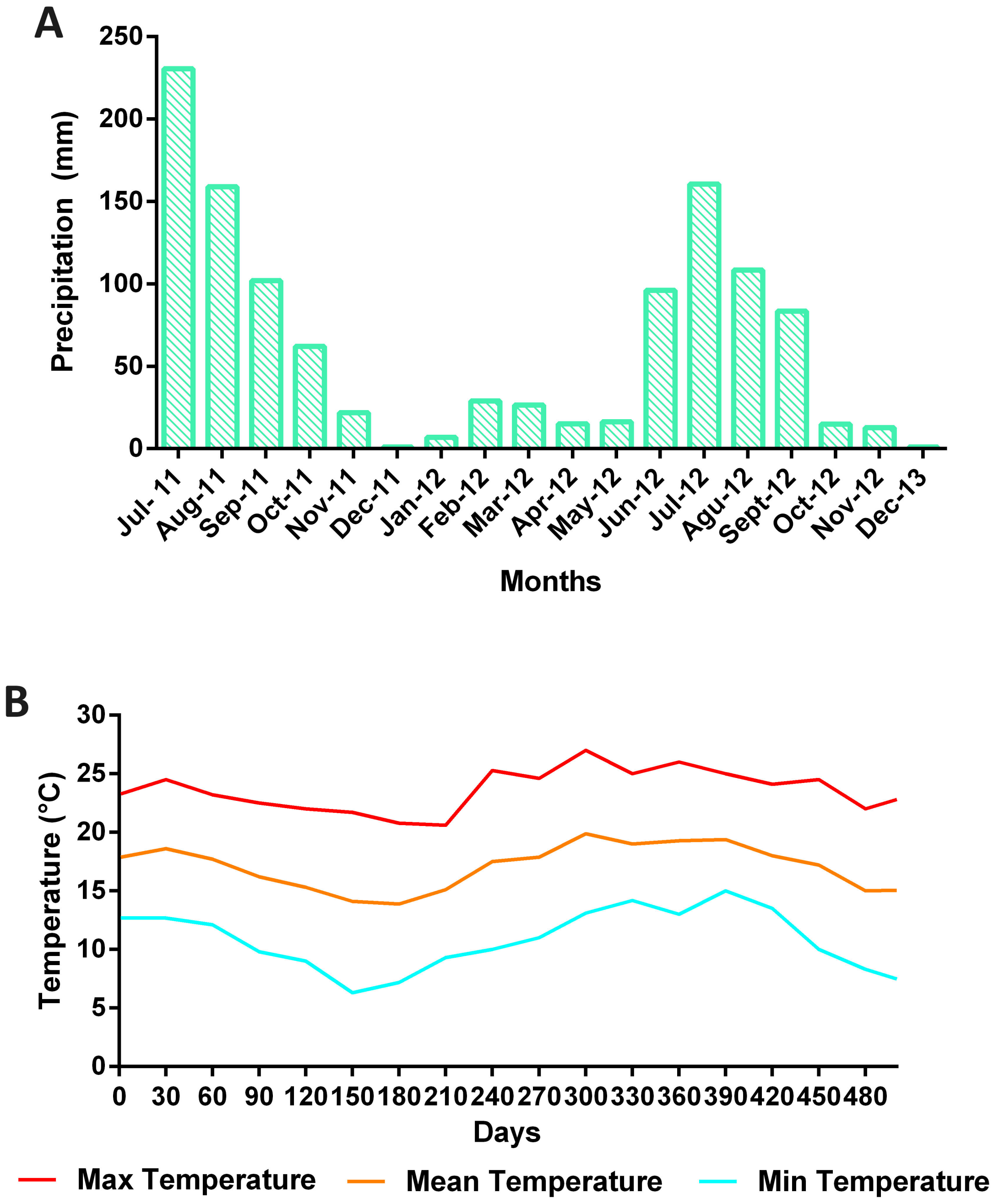


Figure 4.4.1 A) Monthly Precipitation in (mm) from beginning to end of the plant screening. B) Mexico mean, maximum and minimum temperature from day 1 to day 500. Graph based on data from (SMN-México, 2014)

4.4.2 Results and discussion per species

The results of the screening will be presented by species and grouped according to their overall performance on the roof during the screening. Three broad groups will be used to cluster species according to high, medium and low performance, by considering as parameters their survival, diameter RGR, mean diameter, height and percentage of flowering plants. This combined proxies for overall plat vigour and post establishment success will then be used to infer mechanisms underlying the species response and finally a short-list of the most suitable green roof Crassulaceae for Cwb climate (**warm temperate, with dry winter, and warm summer**) green roofs as well as a critique of the robustness of the plant selection methodology model.

4.4.2.1 High performance species

The high performance species are those species display had the best performance in terms of survival, spread, percentage of flowering plants and aesthetics. Species with more than 73 % survival, a final diameter of 10 cm or more, and individuals with 50 % or more of flowering plants distributed throughout the flowering period, are categorized as high performance in the screening.

This includes:

Echeveria agavoides,

E. elegans,

E. gigantea,

E. pringley var. *parva,*

Graptopetalum paraguayense,

Pachyphytum fittkaui

Sedum pachyphyllum.

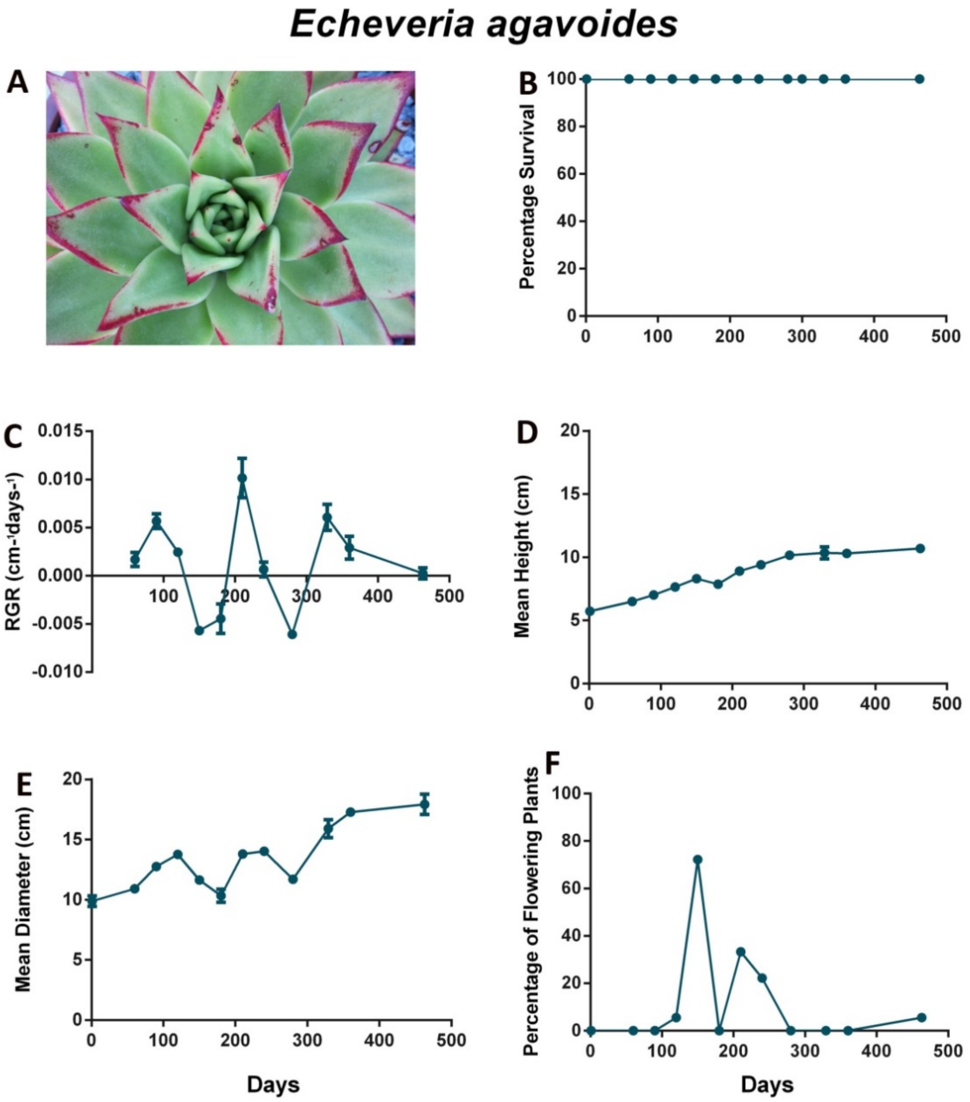


Figure 4.4.2 A) *Echeveria agavoides,* Repeated measures of: B) Percentage survival, C) Diameter Relative Growth Rate, D) Mean Height, E) Mean Diameter, F) Percentage of flowering plants. ±SEM bars only for between depths subjects. Negative RGR is due to shrinking of the species during drought or due to diseases.

Echeveria agavoides

Echeveria agavoides (Figure 4.4.2 A) had a 100 percent survival. This could be related to the very shallow and dry substrates where it grows naturally in regions of the Mexican Plateau (Walther, 1972) (Figure 4.4.2 B). This species, as with the majority of the rosette Crassulaceae plants, shrinks back during the dry season when the plants consume the water stored in their succulent leaves. This phenomenon explains the reductions in diameter after the drought experienced around December (days 150) and April (day 270) (Figure 4.4.2 E). The peak of the flowering period was December (day 150) with plants flowering fairly constantly until February and March (day 210 to 240) (Figure 4.4.2F). This species often grows as a solitary rosette or with very few offsets, and only if the conditions are favourable, will seeds germinate on the roof. For this reason it should probably best be used as an accent plant in green roofs assemblages.

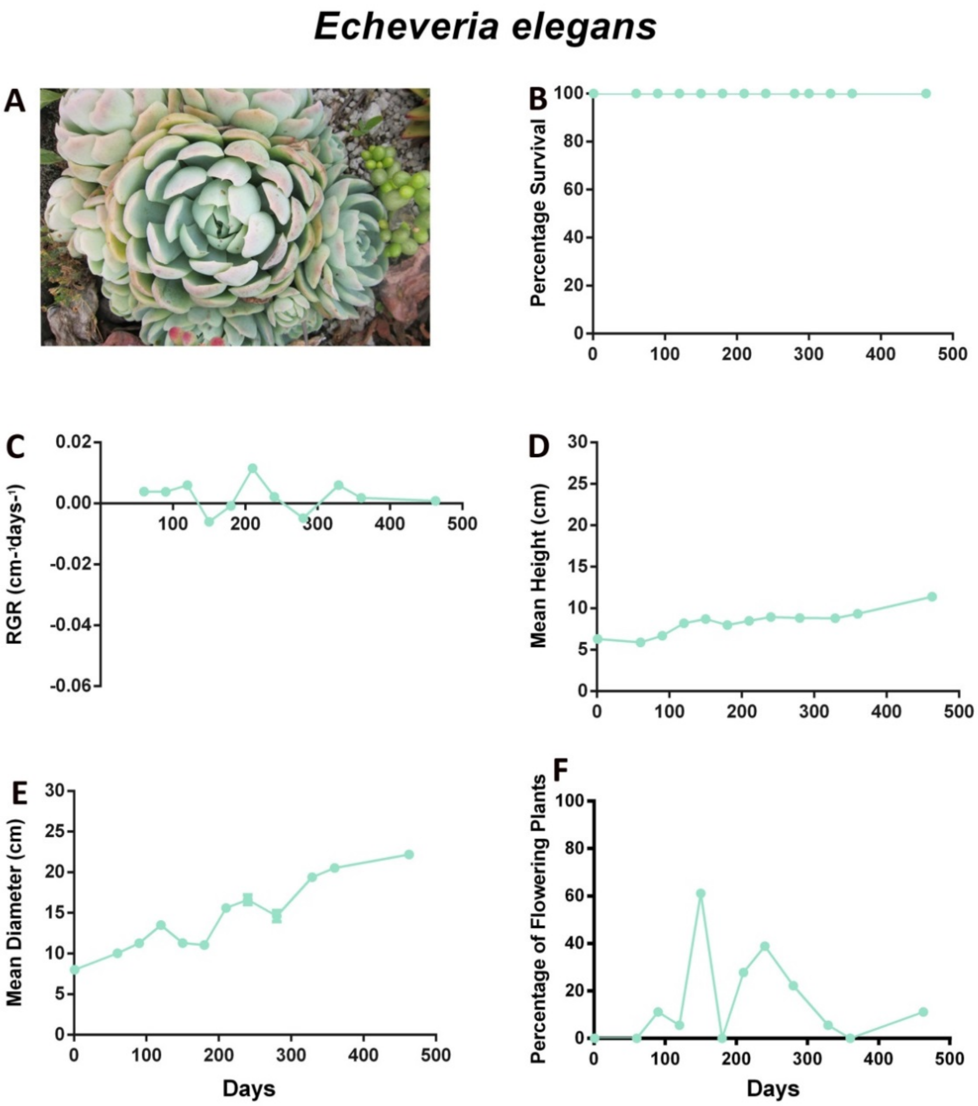


Figure 4.4.3 A) *Echeveria elegans* Repeated measures of: B) Percentage survival, C) Diameter Relative Growth Rate, D) Mean Height, E) Mean Diameter, F) Percentage of flowering plants. ±SEM bars only for between depths subjects. Negative RGR is due to shrinking of the species during drought or due to diseases.

Echeveria elegans

Echeveria elegans (Figure 4.4.3 A) is another species that had a 100 % survival in the screening (Figure 4.4.3 B). This species produces a high number of offsets, which make this a rapid growing species an arguably ideal for the roof in Cwb climates. The rapid vegetative reproduction makes *E. elegans* a useful addition to a new planting. *E. elegans* flowered mainly during December (Day 150), but also from February to April (Days 210 to 270) (Figure 4.4.3 F). Aesthetically this plant has several desirable attributes, due to the colours of the leaves, and flowers and, it's abundant production of pollen and nectar attracts bumble bees and other species of bees.

Echeveria gigantea

Echeveria gigantea (Figure 4.4.4 A) is one of the biggest species of the *Echeveria* genus. It also presented a 100 % survival during the screening (Figure 4.4.4 B). The large size of this species is captured in its high diameter combined with a high RGR (Figure 4.4.4 E, C). During drought this species not only shrinks due to water loss but also discards some leaves. These two traits make its' size highly variable during the year (Figure 4.4.4 E). As with *E. agavoides* it is arguable to use *E. gigantea* as an accent plant and also in combination with shade-tolerant ground cover species to avoid weeds under its' wide canopy. The *E. gigantea* plants flowered mainly during December (Day 150), nevertheless, some individuals flowered during February to April as well (Days 210 to 270) (Figure 4.4.4 F). The colour of the leaves and the tall and bright inflorescence make this species ideal for the roof in terms of aesthetics. In terms of biodiversity benefits this species is highly foraged by hummingbirds, which were observed regularly foraging the plants in the screening plots.

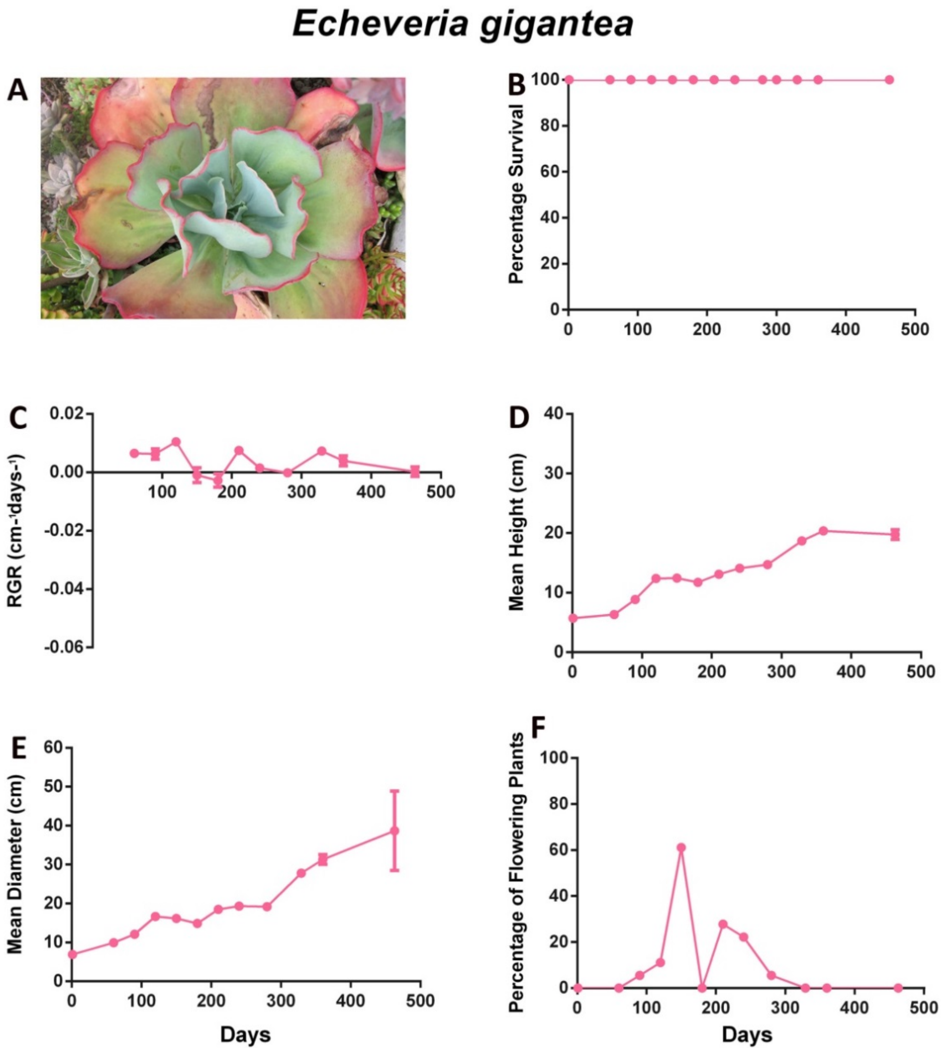


Figure 4.4.4 A) *Echeveria gigantean,* Repeated measures of: B) Percentage survival, C) Diameter Relative Growth Rate, D) Mean Height, E) Mean Diameter, F) Percentage of flowering plants. ±SEM bars only for between depths subjects. Negative RGR is due to shrinking of the species during drought or due to diseases.

Echeveria pringley var. *parva*

Echeveria pringley var. *parva* (Figure 4.4.5 A) presented a 100 % survival in the experiment until June (Day 330) when survival dropped to 88 % and, then, in November (Day 470) to 77 % survival (Figure 4.4.5 B). This observed pattern in mortality could be related to a combination of high competition from other competitive species and the onset of drought that plants were experiencing during the beginning of spring of 2012 (Day 240 to 300) (Figure 4.4.5 B). *E. pringley* is one of the tallest growing *Echeveria* species, which grows to form a small bush (Figure 4.4.5 D). It is therefore a good candidate for growing in combination with ground cover species. During the screening this species flowered, in December (Day 150) and in late winter during February and March (Days 210 to 240) (Figure 4.4.5 F). This species is particularly striking due to the red colourations of the rosette edges of the leaf margins and the bright scarlet flowers. It can vegetatively propagate from fallen stems that root on the ground. Honey bees and bumblebees visited the flowers very frequently during the screening.

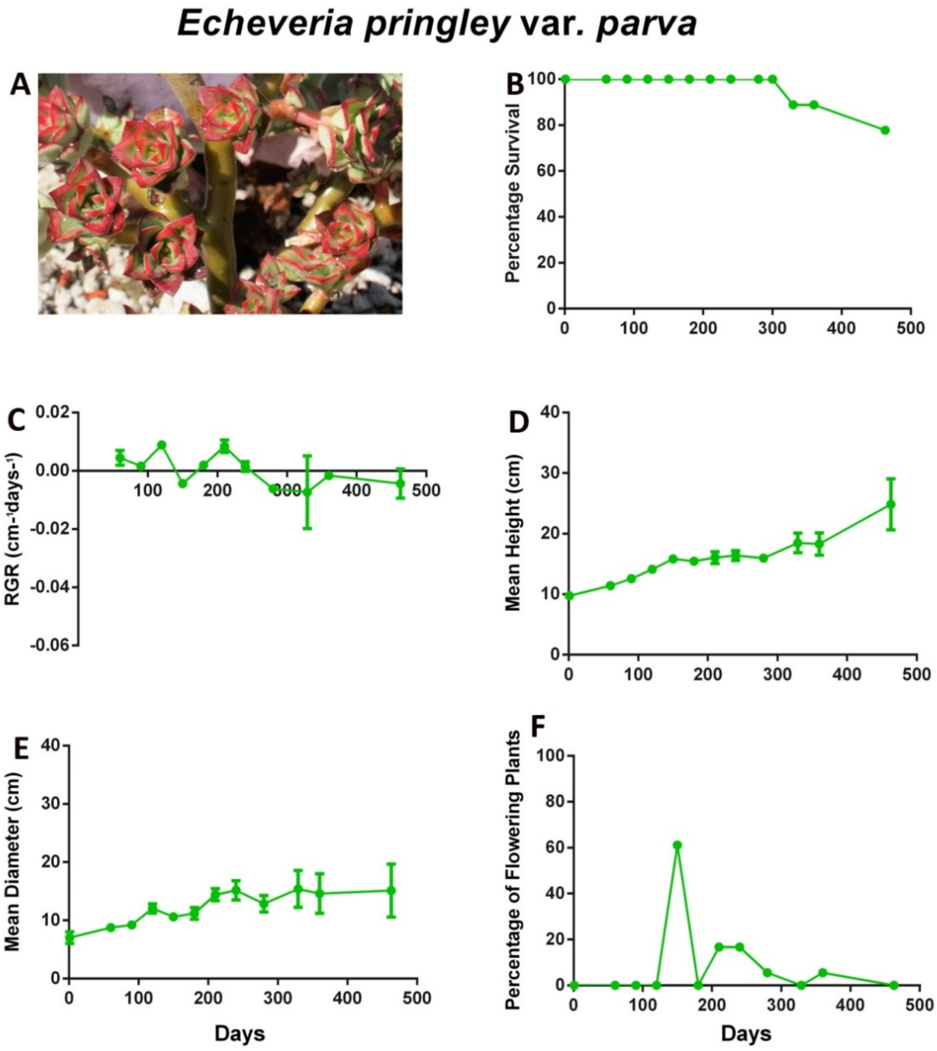


Figure 4.4.5 A) *Echeveria pringley* var. *pringley*, Repeated measures of: B) Percentage survival, C) Diameter Relative Growth Rate, D) Mean Height, E) Mean Diameter, F) Percentage of flowering plants. ±SEM bars only for between depths subjects. Negative RGR is due to shrinking of the species during drought or due to diseases.

Graptopetalum paraguayense ssp. *paraguayense*

Graptopetalum paraguayense ssp. *paraguayense* had 94% survival during the screening (Figure 4.4.6 B). The plants of this species can withstand very extreme drought, and due to its bushy growth form, it can extend across the substrate easily, which makes it ideal for planting on the roofs. *G. paraguayense* usually grows on the side of cliffs in its' native habitat, and therefore the stems are often pendant and new rosette offshoots can root on the ground to readily form new plants. However, the older stems can begin to look leggy. For this reason, it is advisable to use *G. paraguayense* in combination with ground cover species to fill the gaps that the plants can have a tendency to leave behind. Only half of the individuals flowered (55 %) during December (Day 150) (Figure 4.4.6 F), although the flowers are very conspicuous and they are visited regularly by bees.

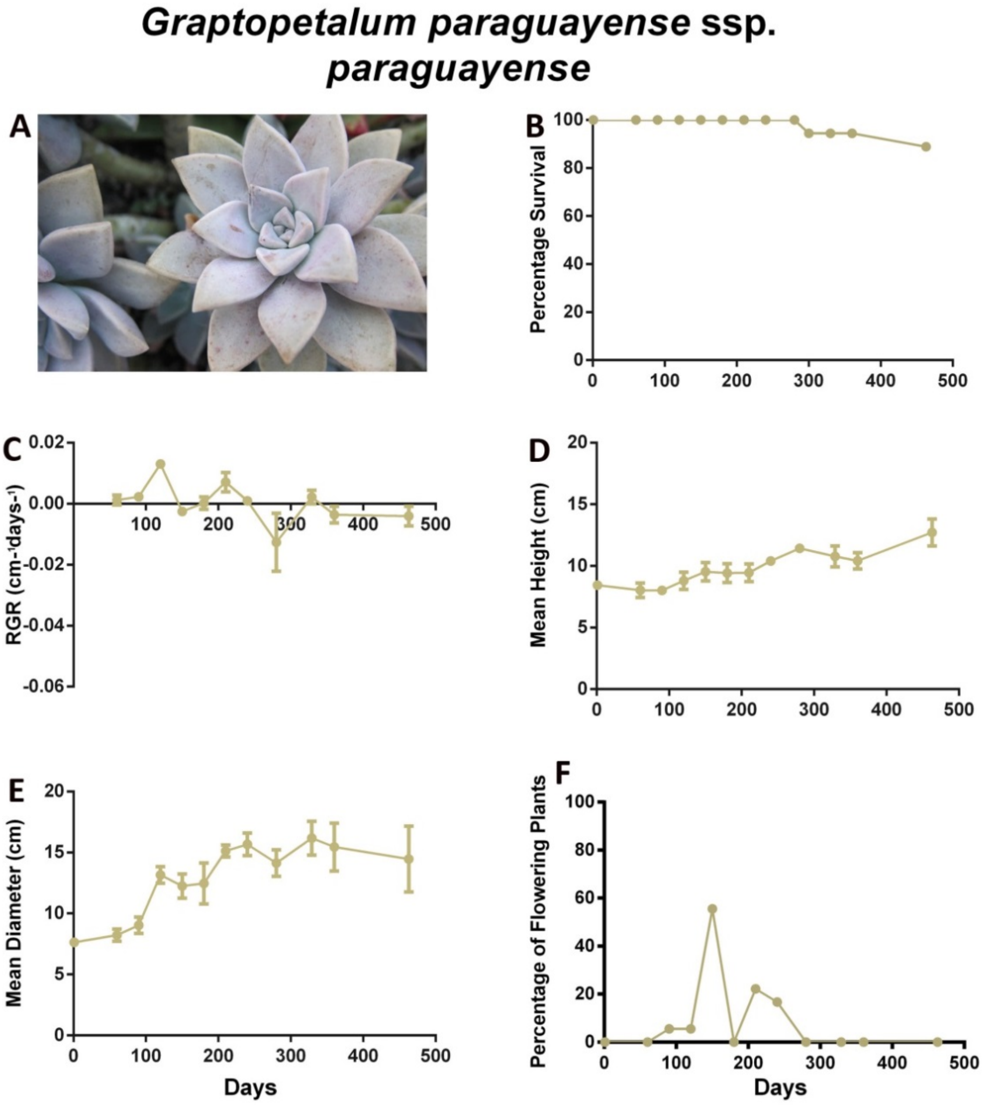


Figure 4.4.6 A) *Graptopetalum paraguayense* ssp. *paraguayense,* Repeated measures of: B) Percentage survival, C) Diameter Relative Growth Rate, D) Mean Height, E) Mean Diameter, F) Percentage of flowering plants. ±SEM bars only for between depths subjects. Negative RGR is due to shrinking of the species during drought or due to diseases.

Pachyphytum fittkaui

Pachyphytum fittkaui (Figure 4.4.7 A) is one of the largest species of the genus and in this screening it was the *Pachyphytum* that had the best overall performance on the roof. It presented a 94% survival, which is probably due to its provenance, on south facing cliff walls in the Mexican Plateau (Moran, 1971). Its' natural habitat is therefore in high intensity sun light and in substrates of very low water retention, highly analogous to the extreme green roof environment. Due to its long leaves, the rosettes reach wide diameters and can be tall (Figure 4.4.7 B, E, D). However, the stem often loses leaves at the base, leaving the ground exposed for opportunistic weeds, hence ground cover species used in combination are advisable. During the screening the flowering period started in December (Day 150) with 60 % of the individuals displaying flowers, and, as with other species, it started again during February (Day 210) probably due to the continuation of the drought in January (Figure 4.4.7 F).

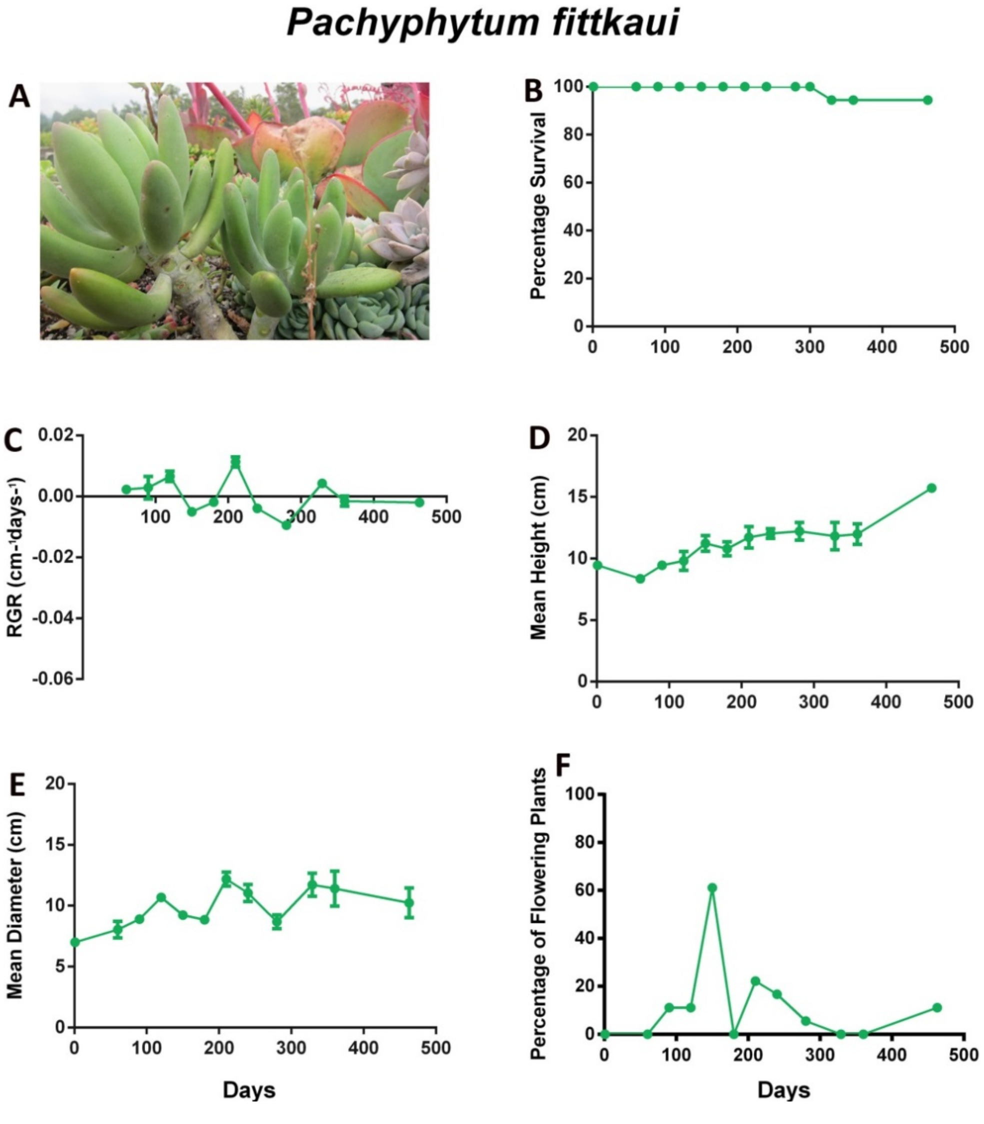


Figure 4.4.7 A) *Pachyphytum fittkaui,* Repeated measures of: B) Percentage survival, C) Diameter Relative Growth Rate, D) Mean Height, E) Mean Diameter, F) Percentage of flowering plants. ±SEM bars only for between depths subjects. Negative RGR is due to shrinking of the species during drought or due to diseases.

Sedum pachyphyllum

Sedum pachyphyllum (Figure 4.4.8A) is native to the arid zones of Oaxaca (Reyes-Santiago et al., 2004). This provenance could be a reason for its' 88.8 % survival in the screening. The bushy species presented a good performance in terms of diameter and had 66% of plants flowering during December (Day 150) (Figure 4.4.8 E, F). Its bright yellow flowers often attracted bees to the roof. This species would be suitable as a ground cover plant if other species are not available, but during prolonged drought it can lose a high quantity of leaves with results in gaps and potential entry pints for colonizing or invasive plants.

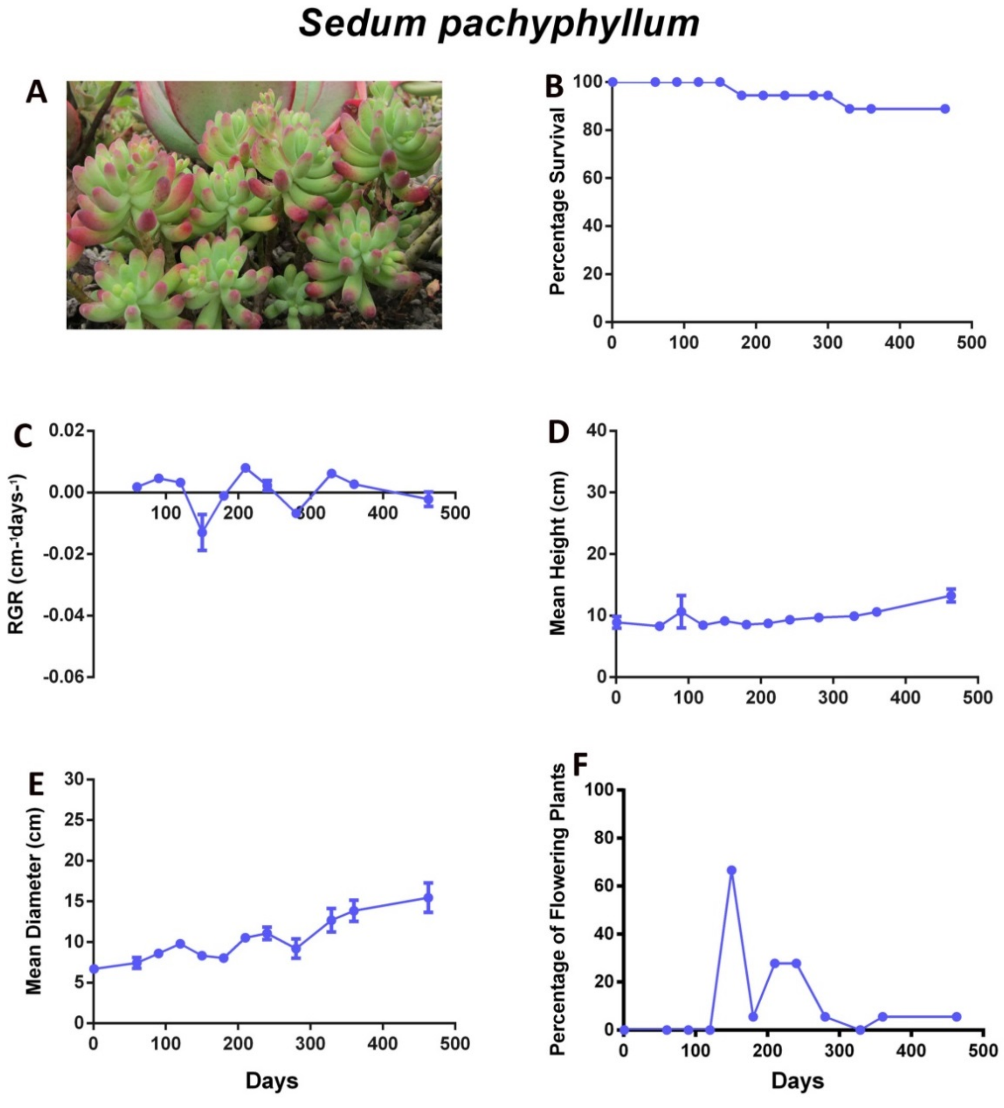


Figure 4.4.8 A) *Sedum pachyphyllum,* Repeated measures of: B) Percentage survival, C) Diameter Relative Growth Rate, D) Mean Height, E) Mean Diameter, F) Percentage of flowering plants. ±SEM bars only for between depths subjects. Negative RGR is due to shrinking of the species during drought or due to diseases.

4.4.2.2 Medium performance species

The medium performance species did not have the best performance in terms of survival, but their mortality rates in figures did not drop below 50 %. Their mean diameter stayed between 5 and 10 cm and presented some aesthetic attributes that still make them good candidates on the roof. This category includes *Echeveria coccinea, Sedum palmeri, S. hernandezii, E. prolifica, E. derenbergii, E. pulvinata, E. shaviana, Graptopetalum superbum, Pachyphytum hookeri, P. werdermannii and* worthy of further investigation perhaps at different sites or in different substrates.

Echeveria coccinea

Echeveria coccinea (Figure 4.4.9 A) survival decreased significantly during the dry periods of the screening, specifically during December (Day 150) and May (Day 300), and at the conclusion of the screening at the end of October and during November (Day 474) (Figure 4.4.9 B). Flowers appeared during December to March, and a small percentage of plants flowered in June (Day 330) (Figure 4.4.9 F). The diameter of this species had a high variation depending on water availability, since some laves can shrink and others fall. Aesthetically, when *E. coccinea* is not flowering it does not present any particularly striking attributes, but it is a desirable species for the green roofs due to its high inflorescence spikes with bright scarlet flowers that attract both hummingbirds and bees. Since plants can become leggy it would be advisable to cut plants down to the base before the rainy season to avoid possible outbreaks of fungal or bacterial infection.

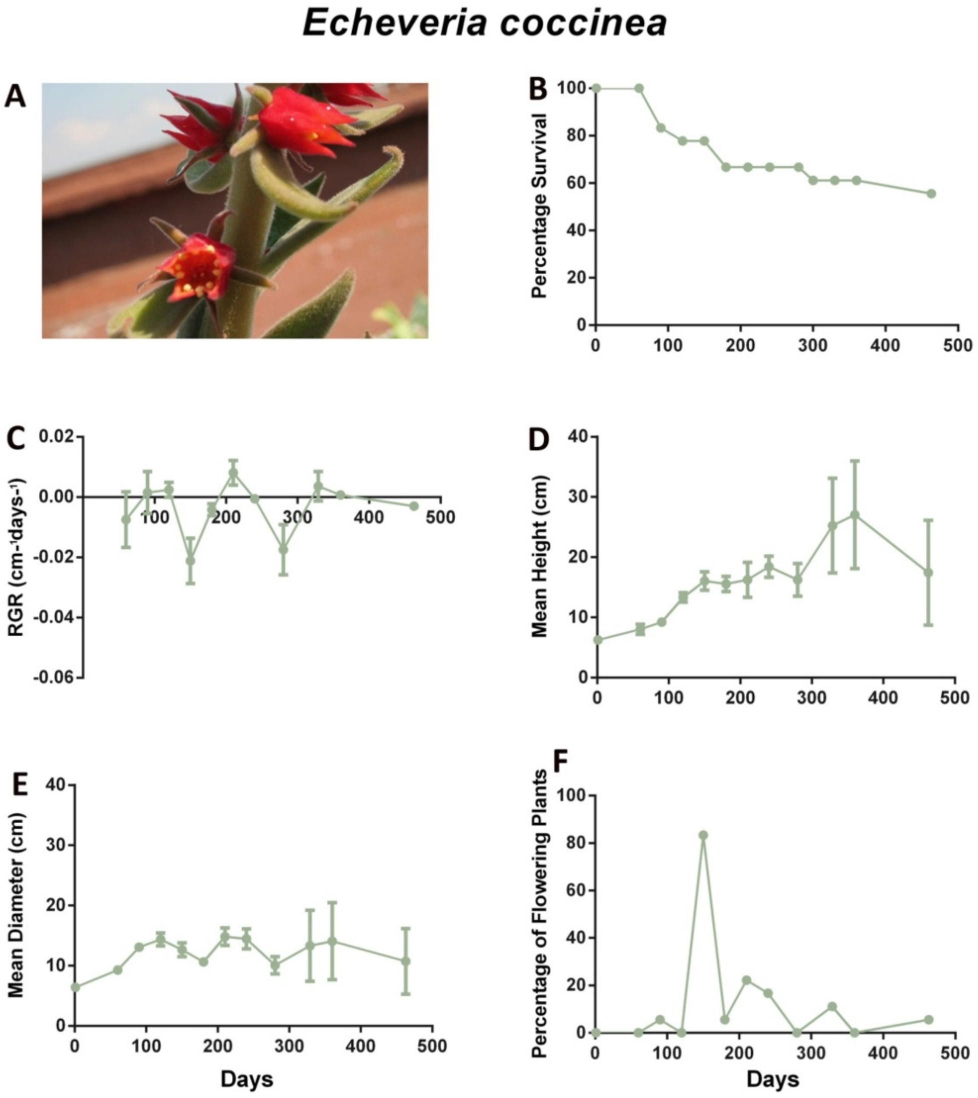


Figure 4.4.9 A) *Echeveria coccinea,* Repeated measures of: B) Percentage survival, C) Diameter Relative Growth Rate, D) Mean Height, E) Mean Diameter, F) Percentage of flowering plants. ±SEM bars only for between depths subjects. Negative RGR is due to shrinking of the species during drought or due to diseases.

Sedum palmeri

Sedum palmeri ssp. *emarginatum* (Figure 4.4.10 A): taxonomically, this subspecies name is no longer in use. Nevertheless, for the purpose of this investigation the subspecies name is used to differentiate diverse forms of the same species. *S. palmeri* had only 50 % survival in the screening, but the plants that survived had a mean diameter greater than 10 cm (Figure 4.4.10 B, E). The high mortality of this species started during the first drought at Day 150, and therefore it is probably advisable to only use this species on roofs that can receive supplemental water with prolonged dry periods. The majority of the plants flowered during December (Day 150), and the flowering period extended up to April (Day 270) (Figure 4.4.10 F). The pale green leaves of this species are very attractive and bees are highly attracted to the flowers. If water is available from other sources during long dry periods it is a very promising species for the roof.

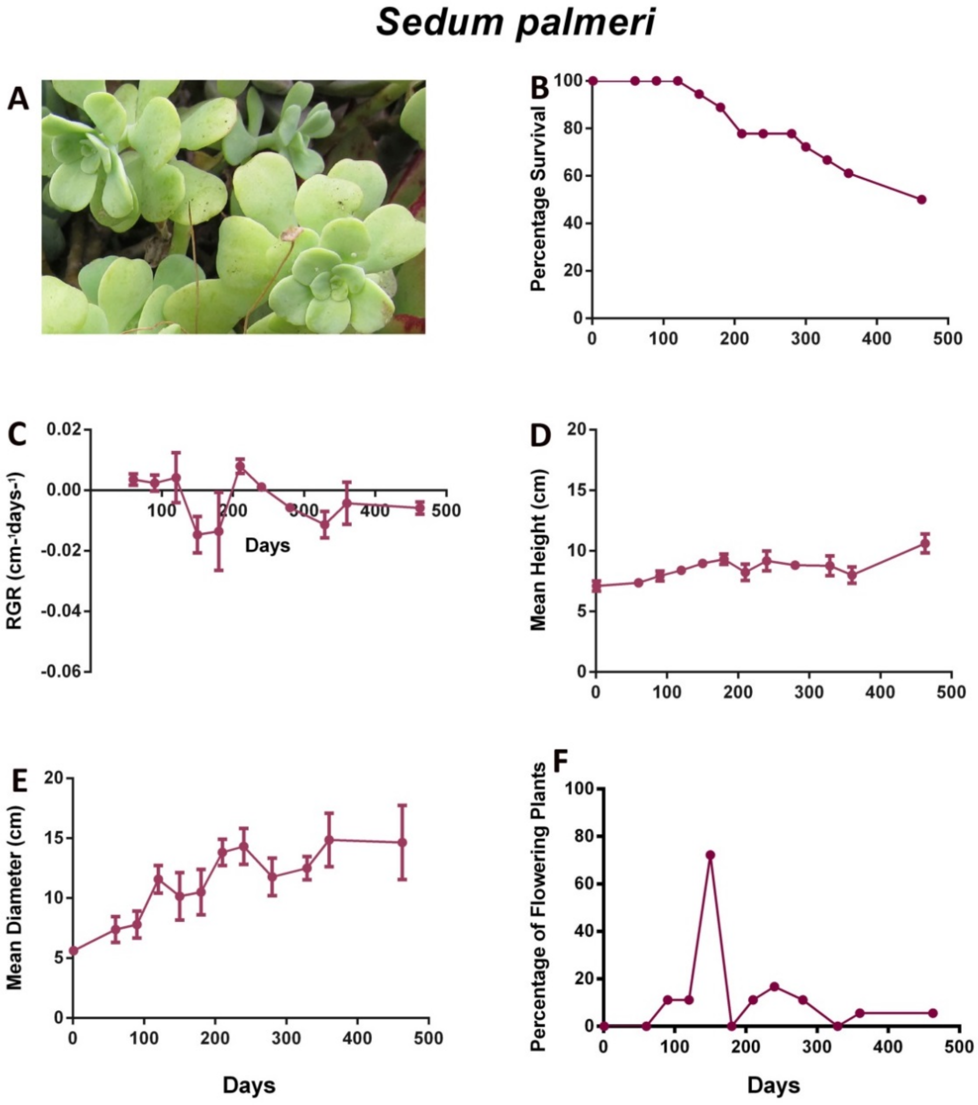


Figure 4.4.10 A) *Sedum palmeri* Repeated measures of: B) Percentage survival, C) Diameter Relative Growth Rate, D) Mean Height, E) Mean Diameter, F) Percentage of flowering plants. ±SEM bars only for between depths subjects. Negative RGR is due to shrinking of the species during drought or due to diseases.

Sedum hernandezii

Sedum hernandezii (Figure 4.4.11 A) is a very compact sedum species, and it had a 72 % survival on the roof (Figure 4.4.11 B). *S. hernandezii* is a stress tolerant plant that grows in its native habitat with no competition on east-facing cliffs, forming big mats. This adaptation to low competition and lower light levels is probably the reason why it did not appear to expand significantly in diameter during the screening. Nevertheless, it is a persistent slow growing species with a high percentage of flowering plants that attract pollinating insects. It could be an ideal plant choice in locations in areas that have some shade during the day (Figure 4.4.11 F).

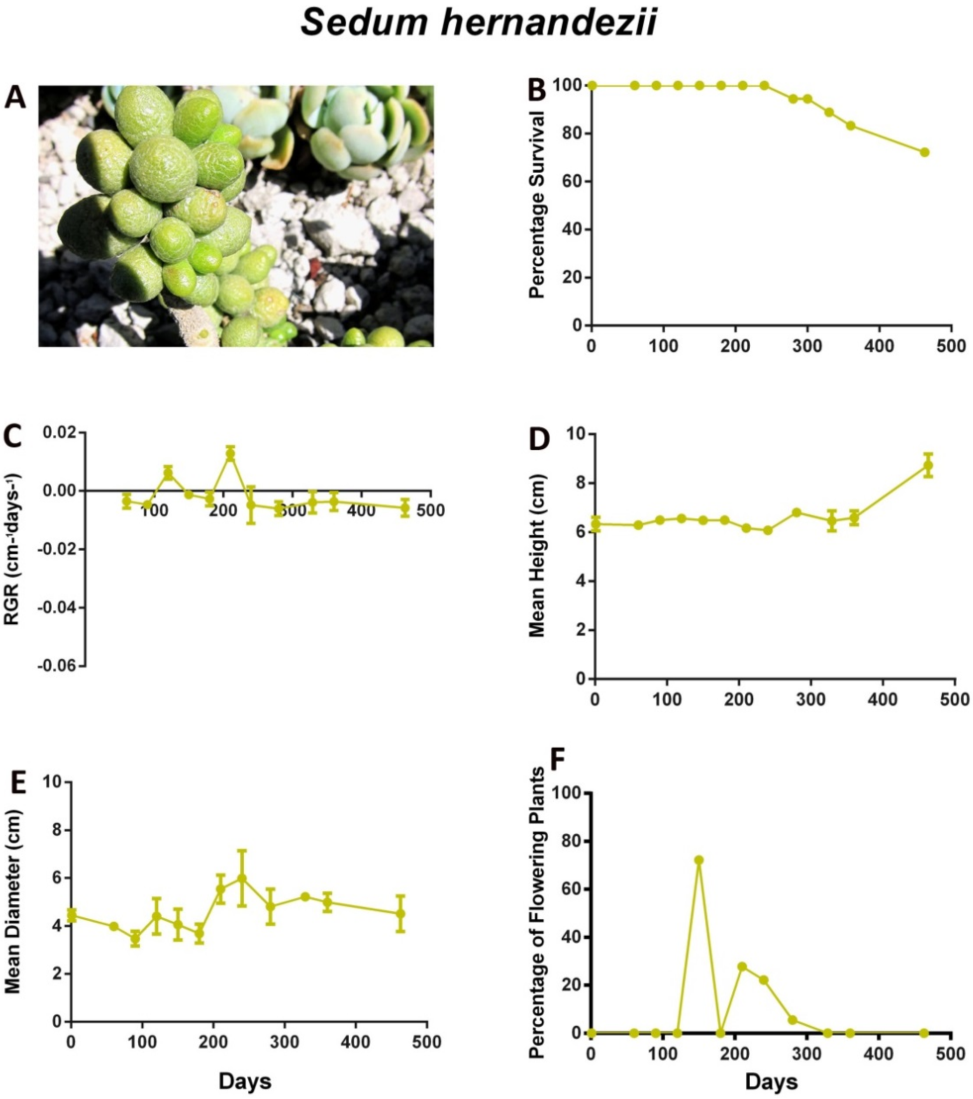


Figure 4.4.11 A) *Sedum hernandezii,* Repeated measures of: B) Percentage survival, C) Diameter Relative Growth Rate, D) Mean Height, E) Mean Diameter, F) Percentage of flowering plants. ±SEM bars only for between depths subjects. Negative RGR is due to shrinking of the species during drought or due to diseases.

Echeveria prolifica

Echeveria prolifica (Figure 4.4.12 A) is another species that established well in the screening, but after Day 330 started to drop in survival. By the end of the screening only 55 % of the plants remained alive (Figure 4.4.12 B). This species can spread quite fast if water is available and if there is supplementary watering during the drought periods (Figure 4.4.12 E), and therefore it could work better in periodically irrigated systems. If water is not available it can die back severally after summer, leaving gaps. The specific provenance of this plant is still unknown to botanists but it was first bought from a nursery in Puebla that claimed that the origin was from a nearby ravine (Moran and Meyrán-García, 1978) in an area of *Pinus* and *Quercus* forests. This suggests this species might prefer to grow in a less exposed area than the roof or on roofs with partial shade.

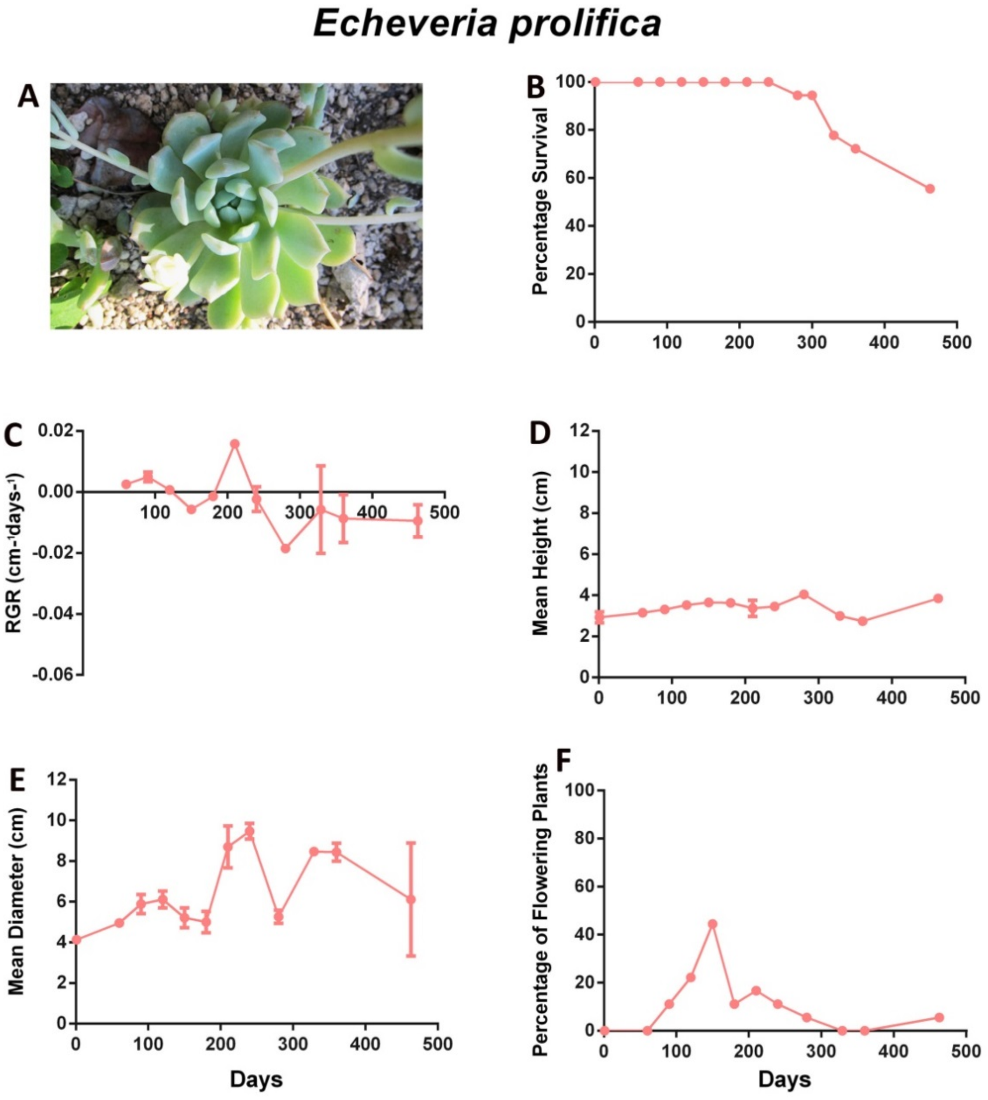


Figure 4.4.12 A) *Echeveria prolifica,* Repeated measures of: B) Percentage survival, C) Diameter Relative Growth Rate, D) Mean Height, E) Mean Diameter, F) Percentage of flowering plants. ±SEM bars only for between depths subjects. Negative RGR is due to shrinking of the species during drought or due to diseases.

Echeveria derenbergii

Echeveria derenbergii (Figure 4.4.13 A) had low survival at the end of the screening, with only 50% of the plants surviving (Figure 4.4.13 B). This could be due to the habit of this small species to grow on cliff walls with minimal competition from other plants. *E. derenbergii* flowered mainly from December (Day 150) to March (Day 240) and only during the last year of the screening some flowers appeared as early as November suggesting that the flowering season might be prolonged for this species (470) (Figure 4.4.13 F).

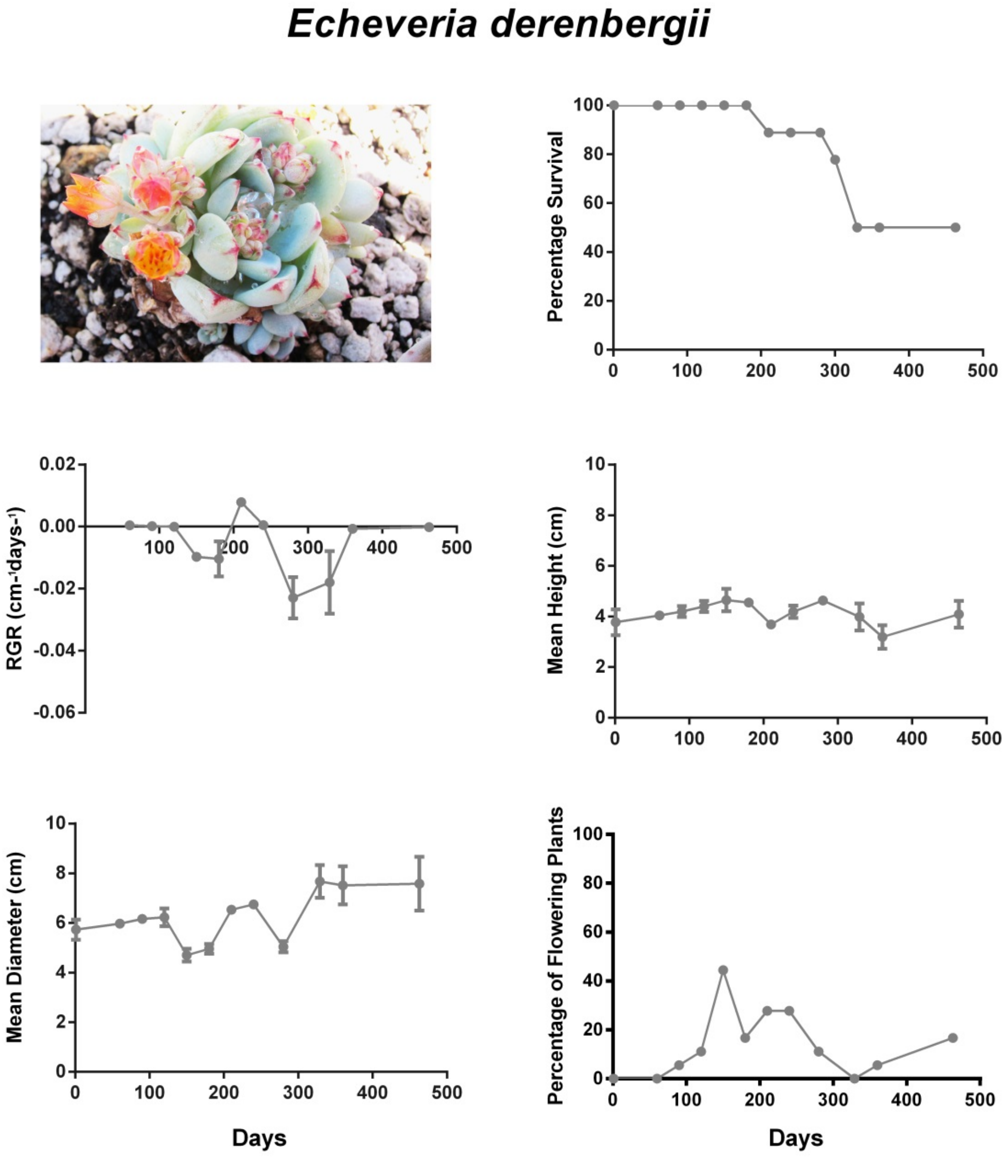


Figure 4.4.13 A) *Echeveria derenbergii*, Repeated measures of: B) Percentage survival, C) Diameter Relative Growth Rate, D) Mean Height, E) Mean Diameter, F) Percentage of flowering plants. ±SEM bars only for between depths subjects. Negative RGR is due to shrinking of the species during drought or due to diseases.

4.4.2.3 Low performance species

The low performance species did not perform well on the roof and had low survival, poor spread, low percentage of flowering plants and/or aesthetics or a combination of various parameters. Their poor performance in this screen, have not exclude them from future green roofs studies in alterative locations.

Echeveria pulvinata

Echeveria pulvinata (Figure 4.4.14 A) is a very beautiful plant but unfortunately it had only 27 % survival. This species is native to a xerophytic area of Oaxaca (Pilbeam, 2008, Reyes-Santiago et al., 2004) where it is used to withstanding droughts. The low survival during the screening might be cause by the unfortunate combination of the planting season and its morphological traits. The species has a large number of dense trichomes on its stems and leaves giving it an unusual fury appearance and texture. The planting and establishment during summer months at the height of the rainy season might have led to a high accumulation of water around the stem that caused the plans to rot since the young and limited root systems were unable to absorb the high quantities of water. It would be advisable to retest this species by planting it prior to summer as this may significantly enhance survival. It produces bright red flowers, which are like its silky leaves, very beautiful and can also attract insect pollinators and birds.

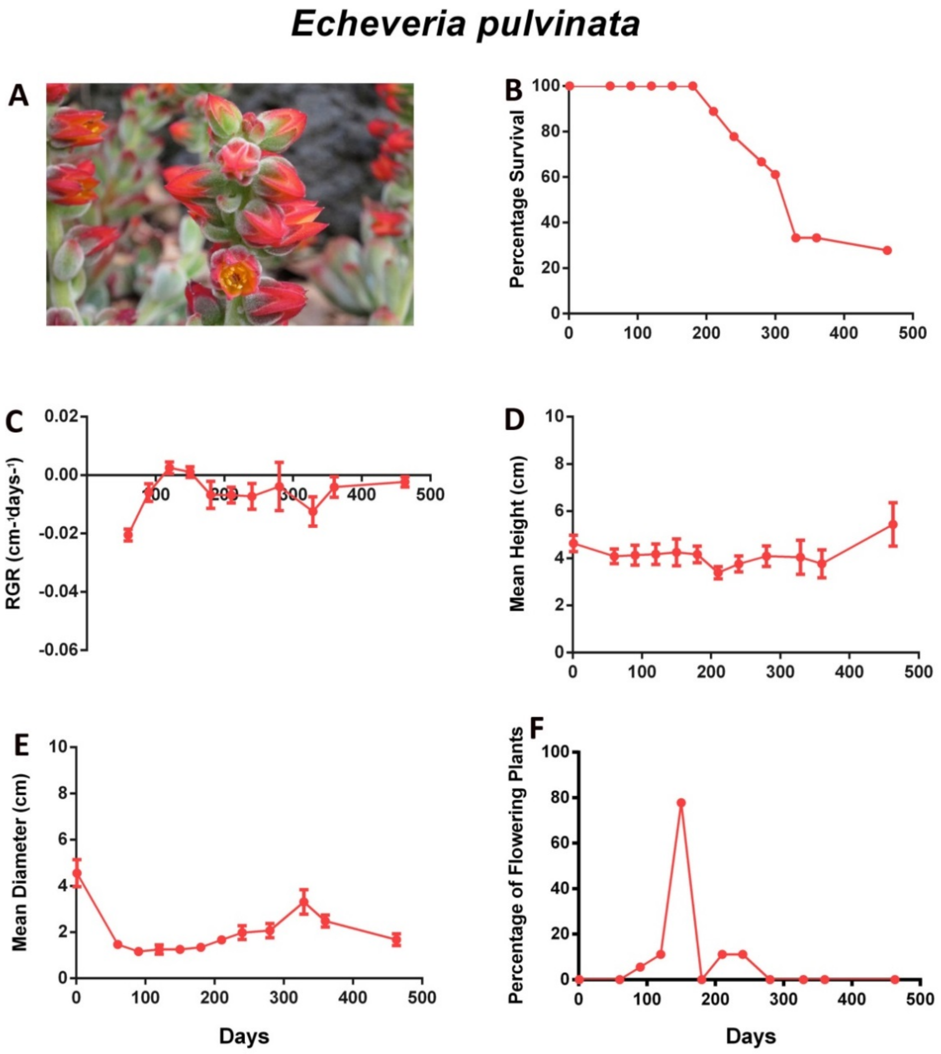


Figure 4.4.14 A) *Echeveria pulvinata,* Repeated measures of: B) Percentage survival, C) Diameter Relative Growth Rate, D) Mean Height, E) Mean Diameter, F) Percentage of flowering plants. ±SEM bars only for between depths subjects. Negative RGR is due to shrinking of the species during drought or due to diseases.

Echeveria shaviana

Echeveria shaviana (Figure 4.4.15 A, B) had the lowest survival out of all the species tested, however that could be due to a poor process of acclimation from their dark storage facility to the full sunlight of the roof. This initial problem might have been a decisive factor in the poor performance of this species, and for this reason it would be advisable for this species to be tested after different acclimation regime. Alternatively if light acclimation was not a factor in this species exceptionally high mortality, then perhaps the plants were not able to withstand the drought. Aesthetically its highly crinkled leaf edge gives it a cabbage-like appearance, so it is unfortunate that it performed so unsatisfactorily.

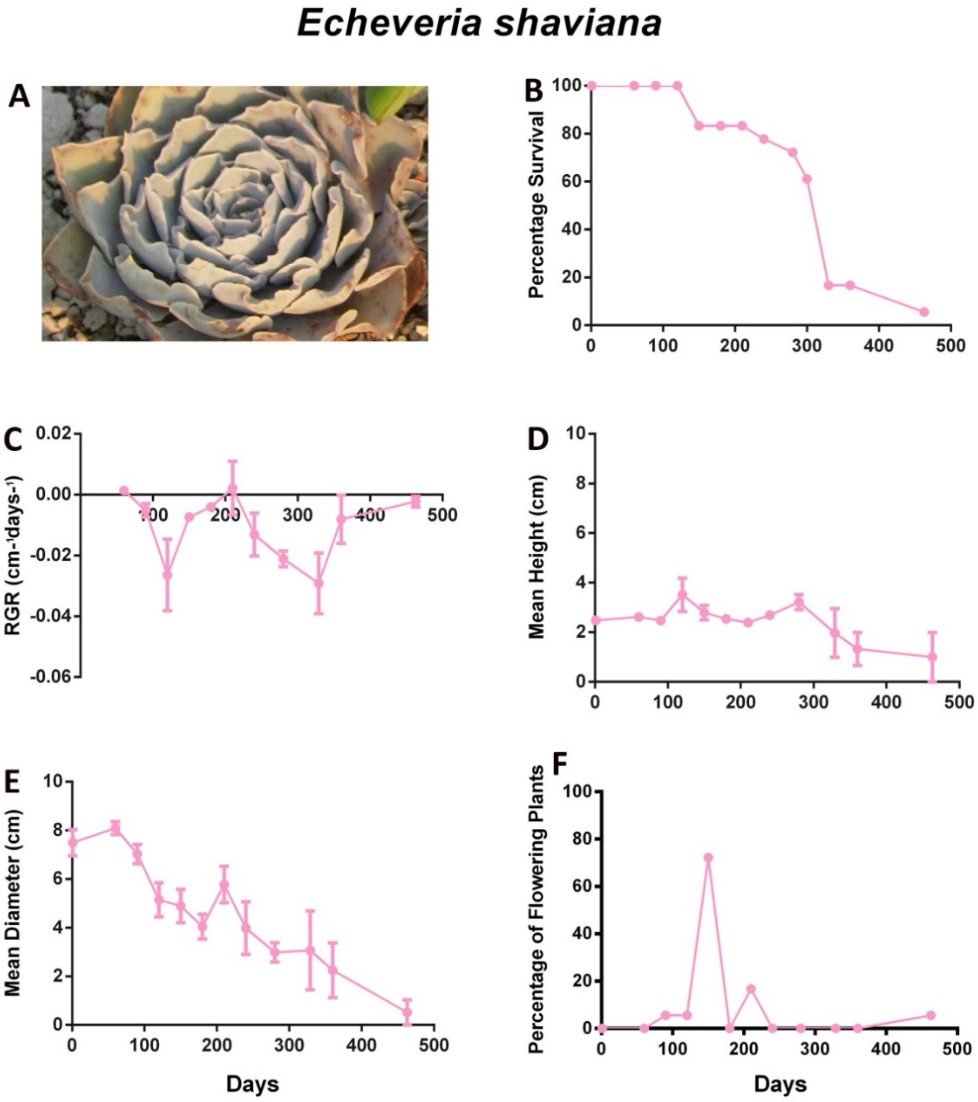


Figure 4.4.15 A) *Echeveria shaviana,* Repeated measures of: B) Percentage survival, C) Diameter Relative Growth Rate, D) Mean Height, E) Mean Diameter, F) Percentage of flowering plants. ±SEM bars only for between depths subjects. Negative RGR is due to shrinking of the species during drought or due to diseases.

Graptopetalum superbum

Graptopetalum superbum (Figure 4.4.16 A, B) had 100% survival up until the first drought when plants started to die. After this survival dropped to 38%. One possible explanation for this drastic drop in survival could be that *G. superbum* grows on east-facing cliff walls (Cházaro Basañes. and Agustín, 1992) and therefore plants receive the sun only during the morning in their natural habitat. This habit might protect the plants from prolonged exposure to the sun and prevent severe dehydration-in stark contrast to the exposed conditions of the roof. This species might therefore benefit from growing on partially shaded areas of the roofs instead. *G. superbum* deep and almost electric blue and purple foliage are powerful additions for the green roof aesthetic palette. For this reason, it would be highly rewarding to grow it as part of an assemblage in les drought and more shaded condition.

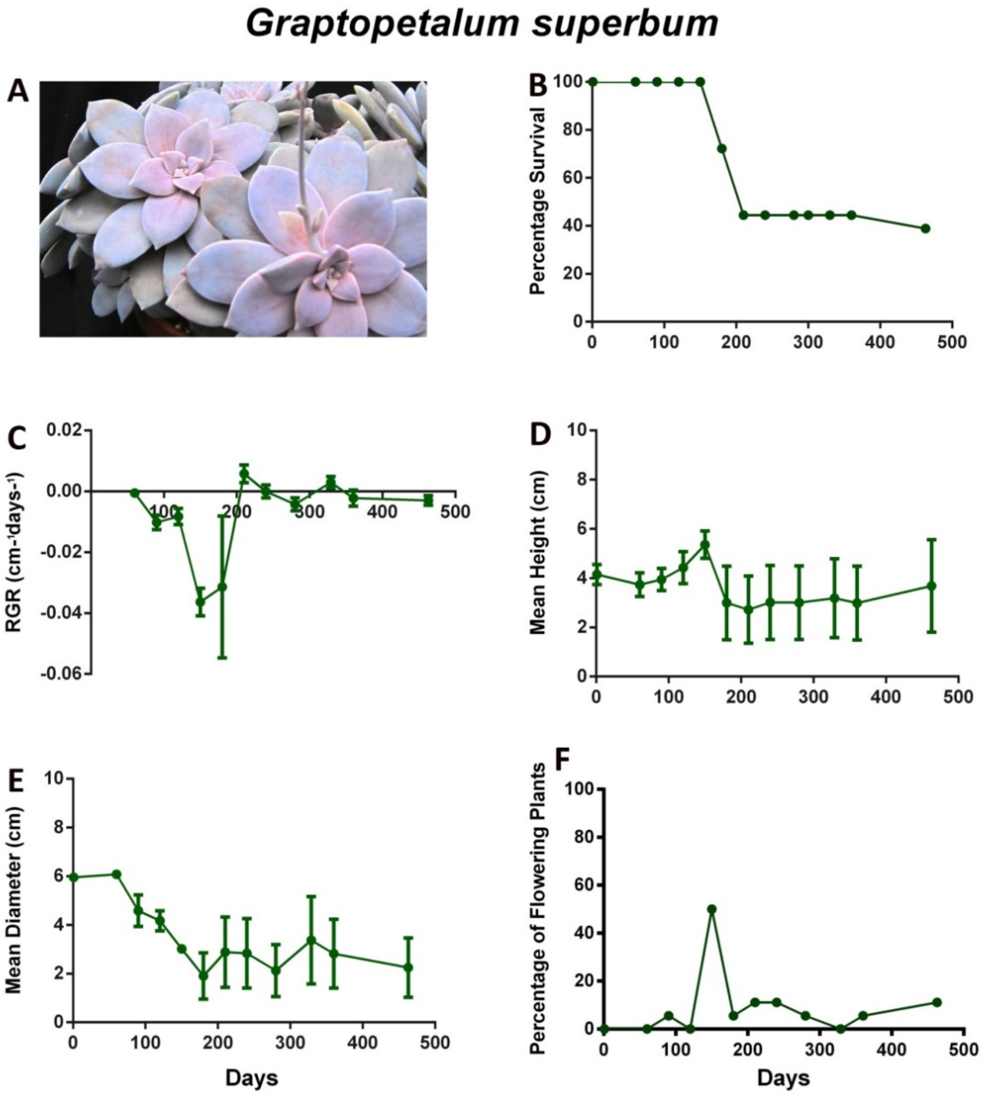


Figure 4.4.16 *Graptopetalum superbum* A) Repeated measures of: B) Percentage survival, C) Diameter Relative Growth Rate, D) Mean Height, E) Mean Diameter, F) Percentage of flowering plants. ±SEM bars only for between depths subjects. Negative RGR is due to shrinking of the species during drought or due to diseases.

Pachyphytum hookeri

Pachyphytum hookeri had a 55.5 % survival in the screening (Figure 4.4.17 A, B). The diameters of the rosettes never grew more than 10 cm (Figure 4.4.17 E). During drought the plants lost several leaves that did not root back and it was never shown its aesthetic qualities, during the whole screening as it continued look very unhealthy. The very poor performance of this *P. hookeri* might be related with it habit of growing on north facing cliff walls in the Sierra Madre Occidental (Moran, 1990). In these native areas the plant is protected from the intense solar radiation for the entire day and it has very few competitors in such semi shaded conditions.

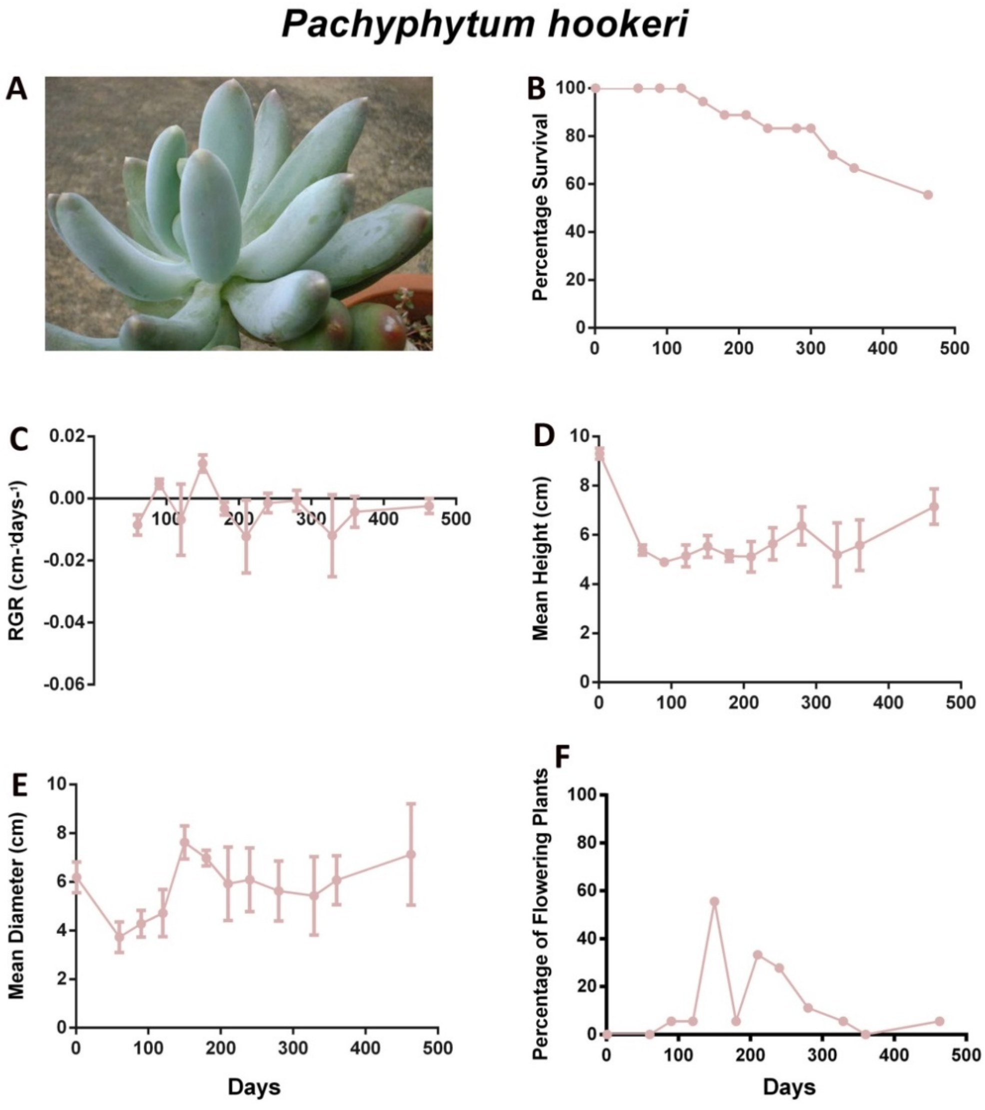


Figure 4.4.17 A) *Pachyphytum hookeri*, Repeated measures of: B) Percentage survival, C) Diameter Relative Growth Rate, D) Mean Height, E) Mean Diameter, F) Percentage of flowering plants. ±SEM bars only for between depths subjects. Negative RGR is due to shrinking of the species during drought or due to diseases.

Pachyphytum werdermannii

Pachyphytum werdermannii (Figure 4.4.18 A) had the same poor performance as *P. hookeri.* In this case the plants grow on walls of cliffs as well, with very little competition from other plants, although the available literature does not specify if plants grow only on north facing walls. Despite of the poor vigour of this species 80 % of plants flowered and the white and pink inflorescence provided nectar and pollen to pollinating insects and birds during December (Day 150) and during June (Day 330) (Figure 4.4.18 F).

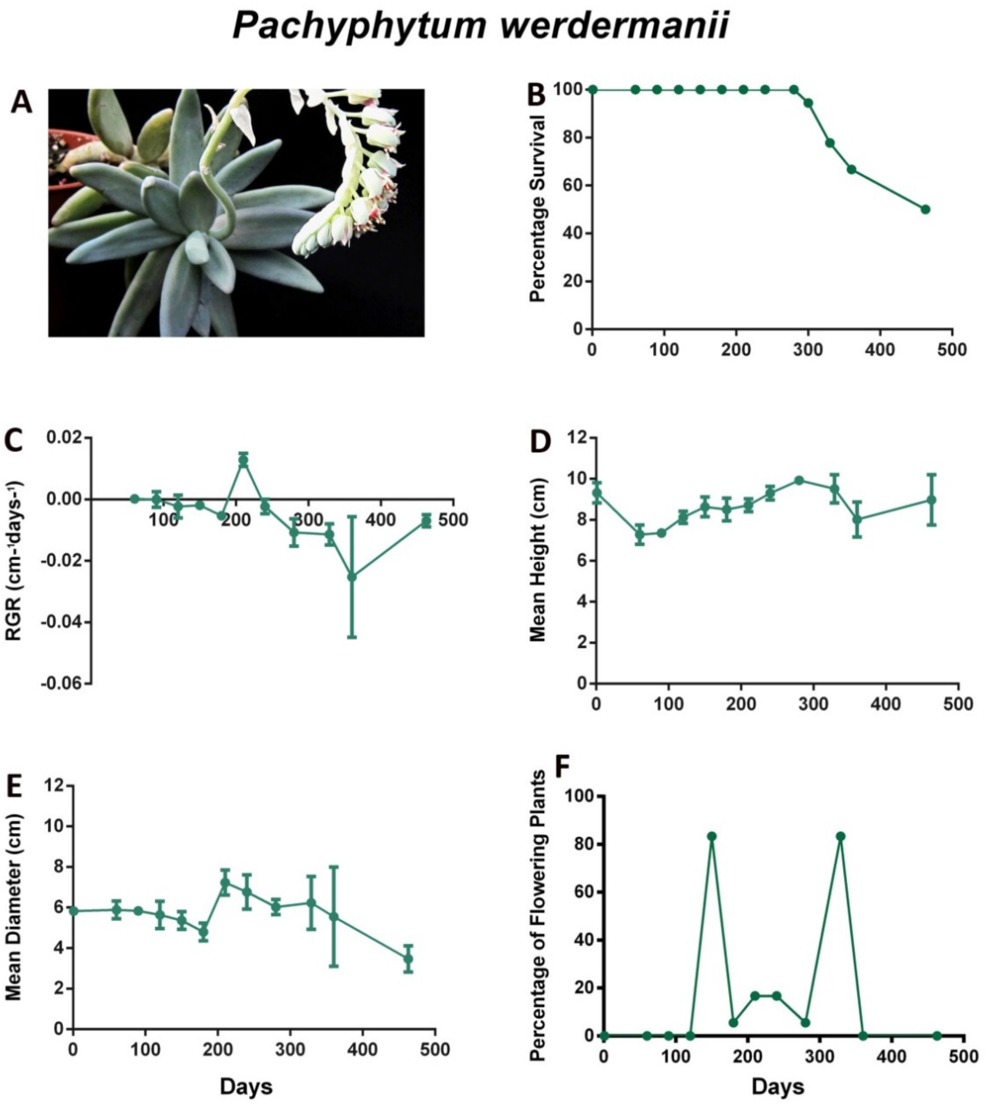


Figure 4.4.18 *Pachyphytum werdermannii* A), Repeated measures of: B) Percentage survival, C) Diameter Relative Growth Rate, D) Mean Height, E) Mean Diameter, F) Percentage of flowering plants. ±SEM bars only for between depths subjects. Negative RGR is due to shrinking of the species during drought or due to diseases.

4.4.3 Results and discussion for pooled species

The screened plants showed a survival of more than 50 percent for the majority of the species. Species like *Echeveria agavoides*, *E. gigantea* and *E. elegans* had a 100 percent survival, while the species with the lowest survival were *Graptopetalum superbum*, *E. pulvinata* and *E. shaviana* with 38%, 27%, and 5 % respectively (Figure 4.4.19).

At the beginning of the screening there was a very low overall mortality rate, probably due to the high amount of water they were receiving at that time (Figure 4.4.20). At day 150, the driest moment of the screening period, the first (and highly significant) reduction in overall species survival was observed (p=0.003)(Figure 4.4.20). At day 280 another significant drop in survival (p=0.033) coincided with more than 100 days of extremely low precipitation. Finally, at day 330, the last significant drop in survival was recorded (p=0.001) (Figure 4.4.20).

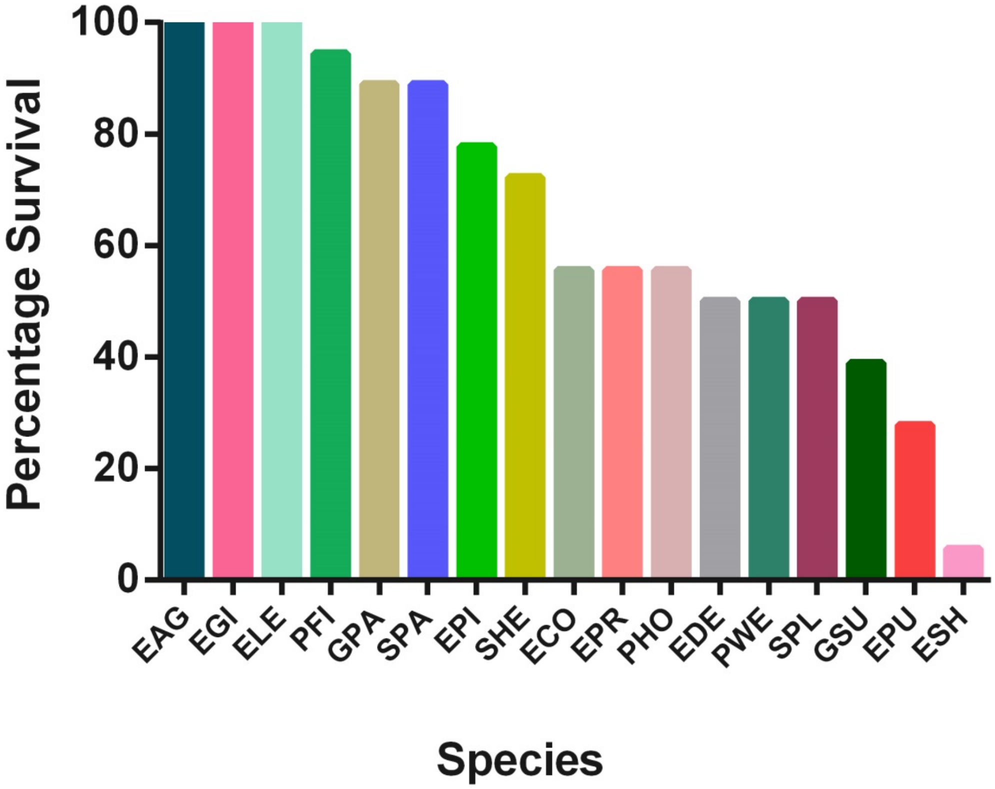


Figure 4.4.19 Final percentage survival of 17 Crassulaceae species (EAG) *Echeveria agavoides,* (EGI) *E. gigantea,* (ELE) *E. elegans,* (PFI) *Pachyphytum fittkaui*, (GPA) *Graptopetalum paraguayense,* (SPA) *Sedum pachyphyllum*, (EPI) *E. pringley* var. *parva,* (SHE) *S. hernandezii,* (ECO) *E. coccinea*, (EPR) *E. prolifica*, (PHO) *P. hookeri*, (EDE) *E. derenbergii*, (PWE) *Pachyphytum werdermannii*, (SPL) *S. palmeri*, (GSU) *G. superbum*, (EPU) *E. pulvinata*, (ESH) *E. shaviana*.

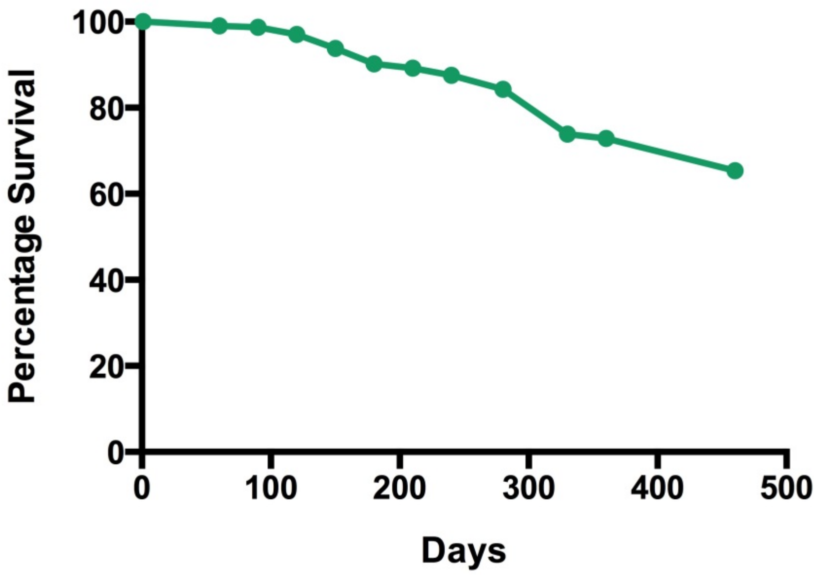


Figure 4.4.20 Combined percentage survival for pooled species per day.

4.4.3.1 Diameter Relative Growth Rate

RGR and rain distribution

The dataset of the diameters relative growth rate shows a very similar pattern to that observed with the precipitation distribution (Figure 4.4.21). A Spearman's correlation test between the diameters relative growth rate (RGR) and the rainfall data shows a moderate significantly correlation between the precipitation and the relative growth rate (r=0.416 n=33 p=0.016). Clearly even though these species are highly drought tolerant, water availability is still the key factor determining growth and survival.

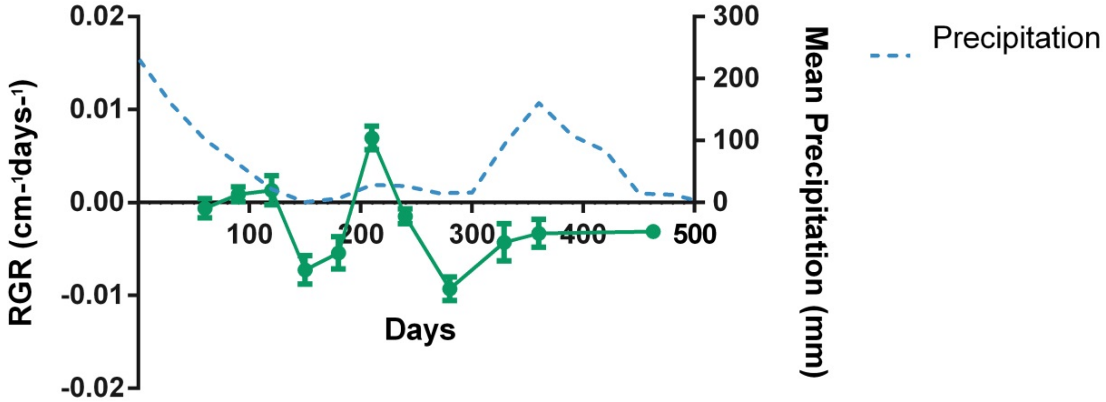


Figure 4.4.21 Mean Diameter Relative Growth Rate for 10 Crassulaceae species and mean precipitation in mm with ± SE. Negative RGR is due to shrinking of the species during drought or due to diseases.

Repeated measures of RGR for all species

The repeated measures of the RGR for all species showed that the first significant change was the decrease of RGR between day 1 and day 150. This change parallels the decrease in rainfall (Figure 4.4.21). The next significant positive increment occurred between day 150 and day 210, which corresponds to an increase in rainfall (Figure 4.4.21). The next significant change in RGR was the decrease between days 210 and 240 and the continuous decline after day 280. Finally, the last significant increment occurred between day 280 and day 463 (Figure 4.4.21) ($p<0.000$). The analysis of RGR shows the irregular growth pattern of plant species on roofs in Cwb (warm temperate with dry winter and warm summer), especially due to their total dependency on rain as a source of water for growth.

Difference of RGR between species

The mean diameter RGR for species showed that the majority of species had a negative RGR. This is probably due to several factors. One factor is the exceptionally low survival of some species like *E. pulvinata* and *E. shaviana*. Only species that had more than 75 % survival were able to maintain a positive RGR. Furthermore, the plants suffer shrinking when dehydrated as this allocates stored water to young tissue, leading to a negative mean diameter RGR.

E. gigantea was the species with the greatest diameter RGR and was significantly higher than either *E. derenbergii, E. pulvinata*, *E. shaviana* or *G. superbum* ($p<0.05$, Tukey HSD) (Figure 4.4.22). *E. gigantea* had the highest RGR of all species in the screening. In summer it grew big leaves but lost several of them with the onset of the severe droughts, and therefore the size of this species change dramatically during the year. The plants remained as solitary rosettes with no plantlets during the screening. Nevertheless, the plots have remained in the roof and new seedlings of this species are now growing in trays near the plots. This is the only species that had successful germination on the roof. *Echeveria elegans* had a significantly higher RGR than *E. pulvinata*, *E. shaviana* and *G. superbum* ($p<0.05$, Tukey, HSD) and produced several plantlets around a mother plant.

The RGR of species like *E. agavoides*, *E. pringley*, *G. paraguayense*, *Pachyphytum fittkaui* and *S, pachyphyllum* had significantly higher RGR means than *E. shaviana* and *G. superbum* ($p<0.05$, Tukey HSD) (Figure 4.4.22). Species *E. prolifica* and *S. hernandezii* had significantly higher mean RGR than *E. shaviana* ($p<0.05$, Tukey, HSD) (Figure 4.4.22); again testimony the very poor performance of *E. shaviana.*

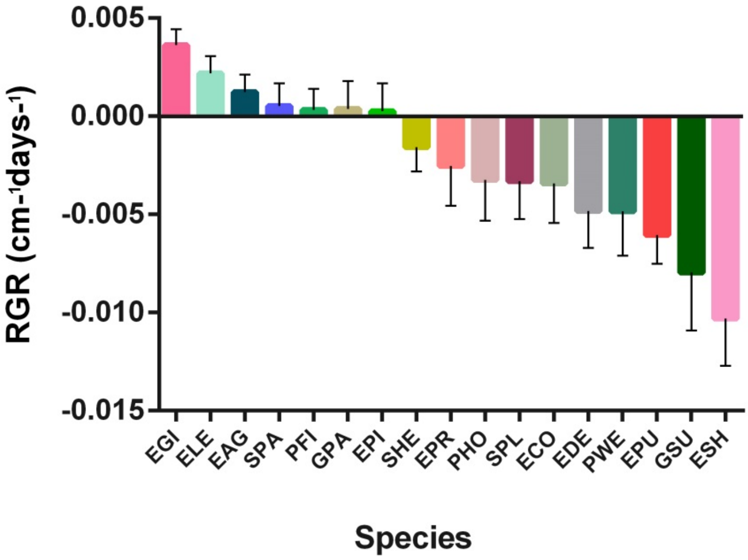


Figure 4.4.22 Mean RGR of 17 Crassulaceae *Echeveria gigantea* (EGI), *E. elegans* (ELE), *E. agavoides* (EAG), *Sedum pachyphyllum* (SPA), *Pachyphytum fittkaui* (PFI), *Graptopetalum paraguayense* (GPA), *E. pringley* var. *parva* (EPI), *S. hernandezii* (SHE), *E. prolífica* (EPR), *P. hookeri* (PHO), *S. palmeri* (SPL), *E. coccinea* (ECO), *E. derenbergii* (EDE), *P. werdermannii* (PWE), *E. pulvinata* (EPU), *G. superbum* (GSU), *E. shaviana* (ESH). Negative RGR is due to shrinking of the species during drought or due to diseases.

4.4.3.2 Diameters

The analysis of the mean diameters for the plants of the screening showed that the first significant increase in diameters for all species was at day 60 ($p<0.05$) (Figure 4.4.23). This change was followed by the increase between days 60 until day 120 ($p<0.05$). Then growth stopped and plants were significantly reduced, probably due to drought at day 150 ($p<0.05$). By day 210, with the return of the rains, growth was significantly re-established ($p<0.05$). The growing period lasted until day 280, when plants were significantly reduced in diameter once more, coinciding with the cessation of rains ($p<0.050$). The diameter growth increased when water was available (Figure 4.4.23) decreased with drought, but, with the return of the rains plants returned to growing until day 360 when a plateau was reached. It is important to note that, at this point, the survival had dropped to around 65%, which suggests that many of these reductions were never able to increase again, because several individuals died. The occurrence of deaths and the drastic shrinking of rosette form plant species necessitates for some external supply of water during the driest months of the year for the optimal growth and performance of green roofs in Cwb climates.

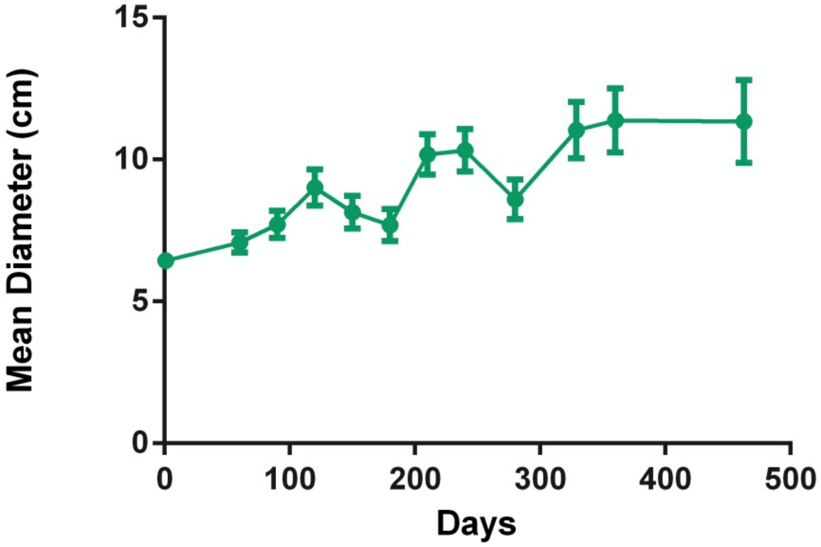


Figure 4.4.23 Combined repeated measures of mean diameter for all species during the screening.

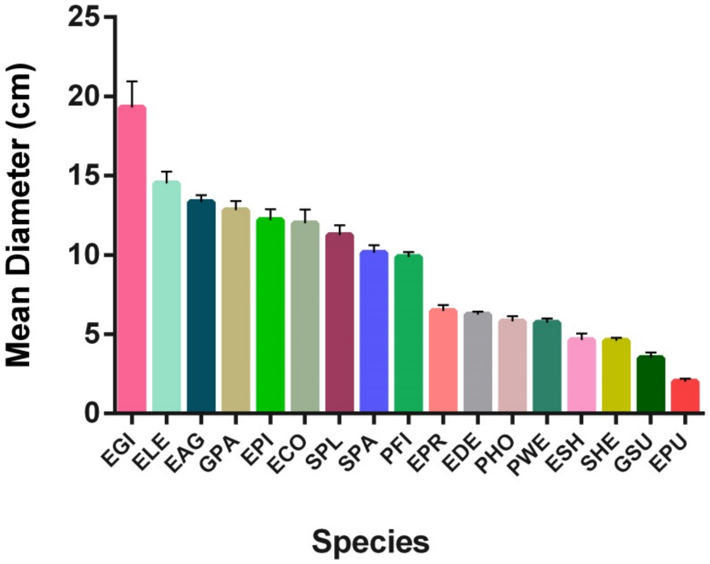


Figure 4.4.24 Mean diameter of all repeated measures of 17 Crassulaceae species: (EGI) *Echeveria gigantea*, (ELE) *E. elegans,* (EAG) *E. agavoides,* (GPA) *Graptopetalum paraguayense,* (EPI) *E. pringley* var. *parva*, (ECO), *E. coccinea*, (SPL) *S. palmeri*, (SPA) *Sedum pachyphyllum*, (PFI) *Pachyphytum fittkaui*, (EPR) *E. prolifica*, (EDE) *E. derenbergii*, (PHO) *P. hookeri*, (PWE) *P. werdermannii*, (ESH) *E. shaviana*, (SHE) *S. hernandezii*, (GSU) *G. superbum*, (EPU) *E. pulvinata*.

4.4.3.3 *Height*

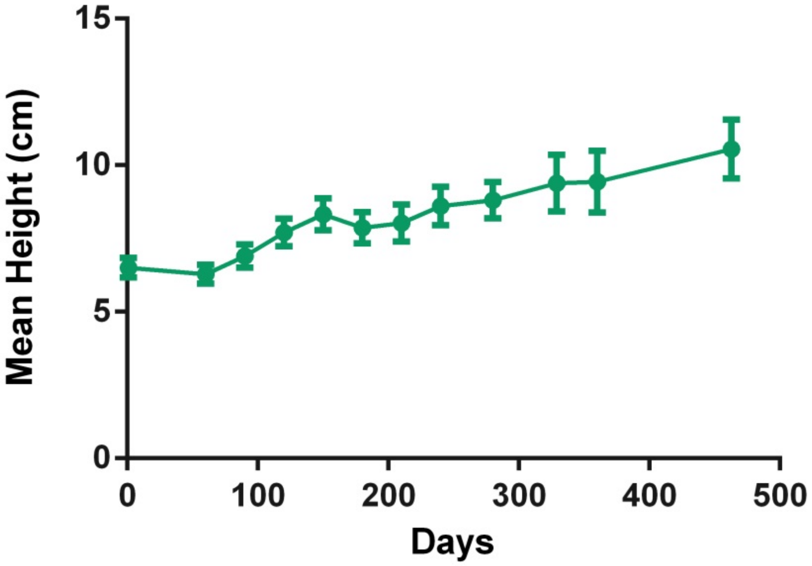


Figure 4.4.25 Combined repeated measures of mean height for all species during the screening.

The first significant increase in combined plant height is from day 1 to day 180 (p=0.005), followed by the increment between day 210 and day 330 (p<0.001) (Figure 4.4.25). The increase between days 240 and 330 was also significant (p<0.001) (Figure 4.4.25), but after this, no more significant changes were found. It is important to note that even though plants can reduce height due to drought, the changes were not as drastic as with the diameter and interestingly none of the reductions in height were significant.

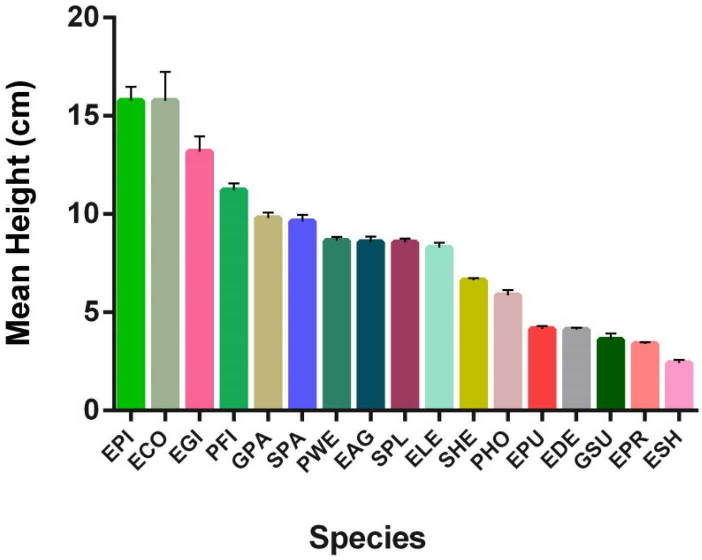


Figure 4.4.26 Mean height for all species of all repeated measures of 17 Crassulaceae species: (EPI) *E. pringley* var. *parva*, (ECO) *E. coccinea*, (EGI) *Echeveria gigantea*, (PFI) *Pachyphytum fittkaui*, (GPA) *Graptopetalum paraguayense,* (SPA) *Sedum pachyphyllum*, (PWE) *P. werdermannii*, (EAG) *E. agavoides,* (SPL) *S. palmeri*, (ELE) *E. elegans,* (SHE) *S. hernandezii*, (PHO) *P. hookeri*, (EPU) *E. pulvinata*, (EDE) *E. derenbergii*, (GSU) *G. superbum*, (EPR) *E. prolífica*, (ESH) *E. shaviana*.

Overall, as can be observed in the combined diameter data, the heights of the plants slowly increased in the plots, showing that despite the extreme environment of the roof and the even more extreme drought episodes, the selected species as a whole were successfully establishing their own green roof community. *Echeveria pringley, E. coccinea,* and *E. gigantea*, were the tallest plant species of the screening. The first two species have a low bushy form, while *E. gigantea* is a rosette form species. Most of the species do not grow more than 10 cm in height (Figure 4.4.26). Nevertheless the flower spikes of *E. coccinea* can reach 30 cm long while the spikes of *E. gigantea* can reach more than 1 m height. The mean height data spread (Figure 4.4.26) shows the diversity in growth form among these four genera of Crassulaceae and may help in the planning of green roofs communities abased on vertical/canopy structure.

4.4.3.4 Flowers

The flowering period of all the pooled species of the screening showed that the peak flowering time is during December (Day 150) (Figure 4.4.27). During January (Day 180) most species practically stopped flowering, and the flowers from December hold their maturing seeds without opening the buds (Figure 4.4.27). The majority of the species restarted their flowering during February (Day 210) and some species extended the flower period into March (Day 240) or even April (Day 270) (Figure 4.4.27). This pause in flowering that was observed across species might be related to the drought experienced at that time and/or the low temperatures experienced during the month of December.

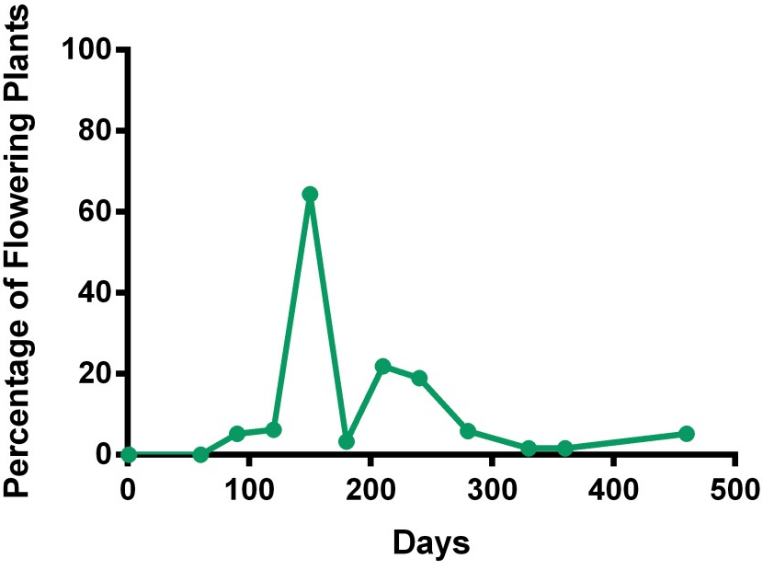
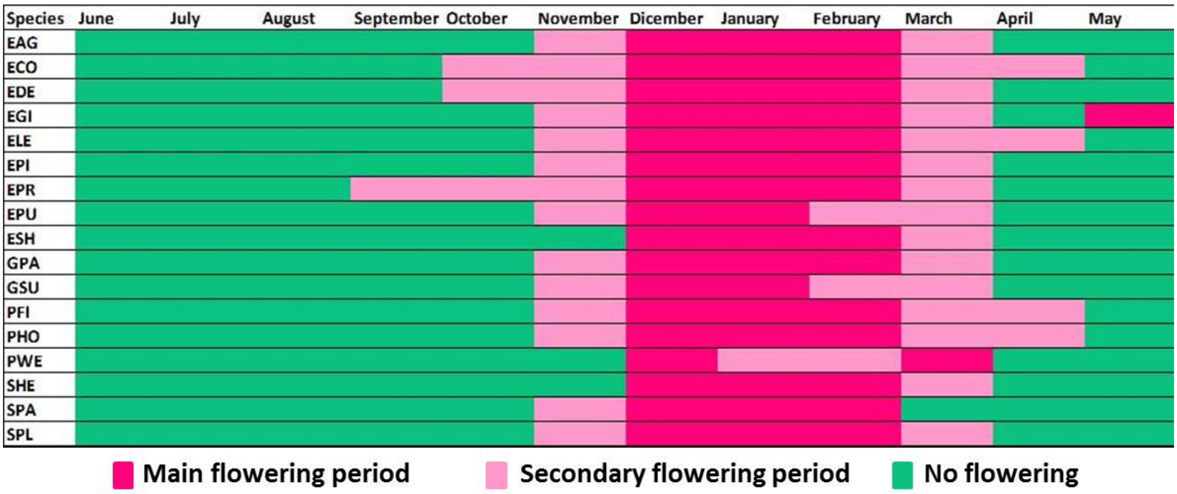


Figure 4.4.27 Repeated measures for percentage of flowering plants for all species of screening.

The distribution of the flowering throughout the year is mainly concentrated through the months of November to April, at this is might relate to the rain distribution. If plants need to produce seeds ready for the summer when rainfall is almost guarantee, the late winter and spring are the crucial moments to produce their flowers. This means that in the most stressful time of the year, in cold and sever drought, most of the Crassulaceae species selected in this screening are required to invest extra energy to produce flowers for reproduction (Figure 4.4.28). This critical timing may go some way to explaining subsequent mortality rates in some species such as *Pachyphytum werdermanii.*



Species	June	July	August	September	October	November	Dicember	January	February	March	April	May
EAG	🟩	🟩	🟩	🟩	🟩	▨	🟥	🟥	🟥	▨	🟩	🟩
ECO	🟩	🟩	🟩	🟩	▨	▨	🟥	🟥	🟥	▨	▨	🟩
EDE	🟩	🟩	🟩	🟩	▨	▨	🟥	🟥	🟥	▨	🟩	🟩
EGI	🟩	🟩	🟩	🟩	🟩	▨	🟥	🟥	🟥	▨	🟩	🟥
ELE	🟩	🟩	🟩	🟩	🟩	▨	🟥	🟥	🟥	▨	▨	🟩
EPI	🟩	🟩	🟩	🟩	🟩	▨	🟥	🟥	🟥	▨	🟩	🟩
EPR	🟩	🟩	🟩	▨	▨	▨	🟥	🟥	🟥	▨	🟩	🟩
EPU	🟩	🟩	🟩	🟩	🟩	▨	🟥	🟥	▨	▨	🟩	🟩
ESH	🟩	🟩	🟩	🟩	🟩	🟩	🟥	🟥	🟥	▨	🟩	🟩
GPA	🟩	🟩	🟩	🟩	🟩	▨	🟥	🟥	🟥	▨	🟩	🟩
GSU	🟩	🟩	🟩	🟩	🟩	▨	🟥	🟥	▨	▨	🟩	🟩
PFI	🟩	🟩	🟩	🟩	🟩	▨	🟥	🟥	🟥	▨	▨	🟩
PHO	🟩	🟩	🟩	🟩	🟩	▨	🟥	🟥	🟥	▨	▨	🟩
PWE	🟩	🟩	🟩	🟩	🟩	🟩	🟥	▨	▨	🟥	🟩	🟩
SHE	🟩	🟩	🟩	🟩	🟩	🟩	🟥	🟥	🟥	▨	🟩	🟩
SPA	🟩	🟩	🟩	🟩	🟩	▨	🟥	🟥	🟥	🟩	🟩	🟩
SPL	🟩	🟩	🟩	🟩	🟩	▨	🟥	🟥	🟥	▨	🟩	🟩

🟥 Main flowering period ▨ Secondary flowering period 🟩 No flowering

Figure 4.4.28 Flower distribution between the months of June to May by species. (EAG) *Echeveria agavoides,* (ECO) *Echeveria coccinea,* (EDE) *Echeveria derenbergii,* (EGI) *Echeveria gigantea,* (ELE) *Echeveria elegans,* (EPI) *Echeveria pringley* subs. *parva,* (EPR) *Echeveria prolifica,* (EPU) *Echeveria pulvinata,* (ESH) *Echeveria shaviana,* (GPA) *Graptopetalum paraguayense* subs. *paraguayense,* (GSU) *Graptopetalum superbum,* (PFI) *Pachyphytum compactum,* (PHO) *Pachyphytum hookeri,* (PWE) *Pachyphytum werdermannii,* (SHE) *Sedum hernandezii*, (SPA) *Sedum palmeri,* (SPL) *Sedum palmeri* ssp. *emarginatum.*

Figure 4.4.29 Screening at day 460 November 2012. *Echeveria gigantea, E. cocciena, and E. pringley* subsp. *parva are* in flower.

Figure 4.4.30 Screening at day 460, November 2012. *Echeveria gigantea,* with hummingbird *Cinanthus latirostris*.

Some species, like *E. elegans,* usually flower in spring from March to April. However in this case, on the roof, the plants flowered first in December and then a lower percentage of plants flowered during spring. *E. coccinea* usually has the peak of its flowering from September to December (Walther, 1972). The obscured alteration of the flowering phenology from that typically displayed on the ground may be a response to the more limited water availability, photoperiod and temperature as well, since plants from dry environments can alter their flowering phenology depending on immediate or prevailing environmental factors (Willert 1992).

Figure 4.4.31 Screening at day 460, November 2012. *Echeveria gigantea, E. coccinea, and E. pringley* subsp. *parva* in flower.

No significant differences in the percentage of flowering plants per species were found. Nevertheless, it is important to stress that species like *Echeveria gigantea*, *Echeveria pringley* subsp. *parva* and *Echeveria coccinea* have the most dramatic display of inflorescences (Figure 4.4.29 and Figure 4.4.30), and as such may provide greater services in terms of aesthetics and food for pollinators like the hummingbirds (Figure 4.4.30).

4.5 Discussion and conclusions

The results of the screening of the selected plants at the 100 mm depth provided key insight into the performance of several Mexican species of the Crassulaceae family to determine which underused members can be incorporated to the plant palette of the Cwb climate. The plants with the best performance were: *Echeveria agavoides, Echeveria coccinea, Echeveria elegans, Echeveria gigantea, Echeveria pringley* subsp. *parva, Graptopetalum paraguayense* subsp. *paraguayense, Pachyphytum fittkaui, Sedum pachyphyllum, Sedum palmeri* subsp. *emarginatum* and *Sedum hernandezii.* The rest of the species had either a poor performance in diameter or survival, or displayed very poor aesthetic characteristics in the roof environment.

It is important to mention that even though the above best species had a good performance on the roof, none of these species has a typical ground cover form, and therefore is advisable to use a combination of mat forming species like *Sedum mexicanum*, *S. moranense,* or *S. reptans* in a community assemblage with the species mentioned above to achieve a major cover of the roof.

The flowering phenology of newly selected species needs to be observed over prolonged periods on the roof to establish if species will established a new flowering period (as in the case of *E. elegans*), or if, after the acclimation of the plants to the roof most, of the species will synchronise flowering during winter. Perhaps these selected green roof species will keep responding to drought, temperature and photoperiods in the same manners and the establishment of plant communities with prolonged flowering over the years will have to be addressed with plant from different families and with different reproductive strategies.

Future projects of green roofs in Cwb climates should involve the incorporation of other plant forms including bulbs, forbs, grasses and perhaps other xerophytes taxa such as Agavaceae and Cactaceae. Projects could address the separated study of different families or the study of particular plant communities. Some of the successful species identified in the screening can be used as indicators of particular habitats with potential species with different life forms, such as grasses or forbs. *E. agavoides* and *P. fittkaui* had exceptionally good performance on the roof, and therefore other species from the pasture lands and natural grasslands of the Mexican Plateau might hold key potential species ideal for the Cwb climate green roof. *E. gigantea* and *E. pringley* var. *parva* also presented a very high performance and both species are from deciduous tropical forests: another habitat which might hold other promising species too. Species from the *Pinus-Quercus* forests were not so successful, with the exception of *E. elegans* that had one of the best performances in the screen. A future multivariate study with more data from the habitat of this species could offer more insight into which areas can have more useful species for the roofs.

Local entomological and faunistic studies in relation to the selected species are important to determine if the suggested plants help to improve the wild-life and biodiversity of the area. In the locality where this experiment was set up, in the south of Mexico City, hummingbirds, mantes, butterflies, bees, spiders, and aphids were all seen in abundance among the selected species. Nevertheless, there were three key factors that might have contributed to the rapid colonization and use of the plants of the roof by these animals. The roof was on a three-storey building (i.e. a low level); the building was situated inside of a botanical garden and the canopy of two mature trees reach the level of the roof. It is highly probable that these combined elements contribute to the use of the screened vegetation by other species, and therefore, is necessary to know whether in different circumstances such as higher buildings, locations in the middle of the city, or the absence of tree canopies at high plant diversity immediately around the building, the plants will provide an equally abundant shelter for wildlife as well.

Chapter 5 Mexican Crassulaceae Screening and planting densities experiments for a Cfb climate: Sheffield, UK

5.1 Introduction

Many green roofs in the UK are long-established. Old roofs like Brian Richardson's roof laid down in 1980s are examples of long term-grass extensive green roofs (Dunnett and Kingsbury, 2008). The UK has a Temperate Maritime Climate or according to the Köpen-Geiger climate classification revised by Kottek, a *warm temperate fully humid with warm summer* (Cfb) (Kottek et al., 2006). Green roofs in this climate are exposed to wet, but not very cold, winters with frost, occasional snow and strong winds. Rainfall is throughout the year with the hottest month being July (Met-Office, 2013). The wide distribution of precipitation during the year in the UK (Met-Office, 2013) is a factor that enables the design of highly bio-diverse green-roofs, in this country, especially for semi-extensive systems.

Nevertheless, extensive roofs in the UK as in other European cities use mainly European *Sedums* in their palette. Most of these species have very much the same growth form. They are ground-cover species, low compact growth, with very small leaves and visually small flowers During dry seasons, some of the European species perform crassulacean acid metabolism (CAM) (See Chapter 2.2)(Dunnett and Kingsbury, 2008, Stephenson, 1994). While these characteristics are desirable for a rapid coverage of the roof, they are also a detriment in terms of biodiversity, and the plants participate minimally in the reduction of runoff, cooling effects and general aesthetics (Dunnett and Kingsbury, 2008). Monocultures of *Sedum* species are usually grown in shallow substrates with no variation in depths. This homogeneous depth and aerial environment does not allow the formation of habitats for invertebrates (Brenneisen, 2003). A low number of total plant species present on the roof has as a consequence a short flowering period on the roof, thereby minimizing the potential of the roof as a food provider for pollinators (Brenneisen, 2005). The low transpiration of many *Sedum* species does not maximize the water uptake of the roof (Lundholm et al., 2010). Despite these negative aspects, it seems that shallow roof systems dominated by these succulents will continue to be used on structures that cannot hold heavy loads, like retrofitted buildings (Dunnett and Kingsbury, 2008). The continuing demand for *Sedum* groundcover, despite its poor reputation, necessities expansion of the *Sedum* (and Crassulaceae) species green roof palette so that the same unwanted characteristics can be minimized.

It is out of the scope of this research to test the efficiency of the selected Mexican Crassulaceae species on roof cooling effects, runoff reduction or their specific impact on biodiversity. Further separate studies will need to be performed to measure the effect of the species in these particular aspects. Nevertheless, the variety of ground forms, plant shapes, sizes and arrangement of leaves of some of the Mexican species might have a positive impact on the attraction of invertebrates. As Brenneisen (2003) has shown, different soil and plant structures can increase the number of invertebrates on roofs and, therefore a first step to improve the properties of existent and future *Sedum* extensive green roofs is to look for species with a variety of forms and shapes. Aesthetically speaking, the wide diversity of colours of leaves and flowers from the selected Mexican Crassulaceae, their structure and textures make them strong candidates to incorporate as part of plant communities for both extensive and semi-extensive roofs. Therefore, the testing and research of targeted Mexican Crassulaceae species for green roofs in Cfb climates, like UK, is highly relevant to improve the characteristics and services of shallow green roofs in this climate. It is important to underline that not all Mexican Crassulaceae species will be able to survive in a Cfb climate, since these plants originate from a wide range of native habitats in Mexico, as seen in Chapter 2. Some species are not hardy enough to withstand the lower temperatures of the Cfb climates in comparison to the habitats in which they evolve. Nevertheless, the plant selection methodology of this study was designed with the aim of targeting those areas with the most similar climatic characteristics to that of the Cfb, with the hope of finding suitable Mexican Crassulaceae species candidates to add to the plant palette of areas with Cfb climate, like the UK.

This Chapter has three main sections. The first section (5.2) presents the methodology, results and discussion of a screening of a total of twenty-five species and six different species ecotypes/varieties of the *Echeveria, Graptopetalum, Sedum* and *Pachyphytum* genera. Section 5.2 provides a general view about the survival and growth of these Mexican Crassulaceae species on green roofs in a Cfb climate. For this first approach to the Mexican Crassulaceae species it was important to observe the survival and performance of the selected species under uniform conditions at the roof level. The screening had the aim of targeting the most successful species in terms of survival, diameter growth, vertical growth and overall aesthetics. In the second section (5.3) the species that presented a good performance in the preliminary screening further tested through a competition experiment with European species planted at different densities, to understand their interactions with European *Sedum* species commonly used on green roofs, as well as to determine the optimal densities for establishment. The third section (5.4) presents the conclusions of these experiments and discusses the analysis and potential use of the selected Mexican Crassulaceae species in Cfb climates.

The main questions of this chapter are:

1) Can the Mexican Crassulaceae species targeted with the plant selection methodology of Chapter 2 survive on green roofs in a Cfb climate.
2) Can the targeted Mexican Crassulaceae species have a good performance on green roofs in a Cfb climate?

3) Can Mexican Crassulaceae species cohabit with generally used Crassulaceae species on green roofs in a Cfb climate?
    a) Which density-per-space unit of the Mexican species and the European species can provide a mutualistic interaction?

4) According to the survival and performance of the plant species tested in the screening, did the methodology accomplish and serve its' purpose of targeting species with potential to be used in Cfb climates?

5.2 Screening of 25 Mexican Crassulaceae ecotypes on a green roof in a Cfb climate

5.2.1 Methods and Materials

A screening to determine the survival and performance of twenty-five ecotypes of the genera *Sedum*, *Graptopetalum*, *Echeveria* and *Pachyphytum* in the microclimate of a green roof in Sheffield, UK, was set up in May 2011 and ran until July 2013 on the roof of the 8 storey building of the School of Education of the University of Sheffield.

The plant material for the screening was obtained from diverse sources. The majority of the mother plants of *Sedum* and *Graptopetalum* species were propagated from cuttings donated by Ray Stephenson off the UK National Collection of *Sedum.* The mother plants from the *Echeveria* and *Pachyphytum* genera were bought from Norbert Kleinmichel's *Atomic Plant Nursery* as well as from John Pilbeam's Nursery. Some mother plants of the *Pachyphytum* genus were donated by Jerónimo Reyes, curator of the Mexican National Crassulaceae Collection and were imported into the UK with a phytosanitary certificate. All plant material for the screening was propagated in a research greenhouse of the Sheffield Botanical Gardens.

Cuttings of the *Sedum* mother plants were grown for 7 months in a greenhouse of the Sheffield Botanical Gardens. *Echeveria, Pachyphytum* and *Graptopetalum* species were propagated by leaf cuttings or offsets. Leaves and offsets were rooted on top of trays filled with 4 cm of J. Arthur Bower's Cactus Compost. In April 2011, when the mother plants were mature, the preparation of the cuttings for the roof was initiated. For *Sedum* and other bushy species shoots of 7 cm long were cut, leaves of the bottom 4 cm of the shoot were removed, as well as any flower buds. Cuttings were left to heal for five days in order to produce callous tissue to present possible infection. Once healed, cuttings were planted in plug trays of 20 x 20 x 55 mm in with a mix of 80% J. Arthur Bower's Cactus Compost and 20 % grit of 3 cm deep. Small rosettes were propagated from leaves and offsets were planted in plug trays of 34 x 34 x 65 mm cells using the same media mix. Cuttings and rosettes were rooted for 6 weeks inside the greenhouse and then during 2 weeks more plants were gradually acclimatized to the exterior. The first week plants were placed in the sheltered exterior between two greenhouses, which protected the plants from wind currents, and in the next week they were allocated an area with only one wall protecting the plants from the wind. After this period, plants were transported to the roofs where the screening experiment was then set up.

On the roof, the screening was set up with three replicated units of trays. Each unit was formed using six plastic trays organised in a two by three grid, facing North with no shading from adjacent buildings. Each plastic trays was 73.5 cm x 42.5 cm x 16 cm, with a 15 mm diameter drainage holes in each corner, and a 3 mm drainage grid. Each tray contained a polystyrene layer of 50 mm to raise the surface level of the substrate to the same height as the growing tray, avoiding shading from the sides. The polystyrene layers possessed a 15 mm diameter drainage hole in each corner. Each tray contained a Zinco drainage layer (DVB-12), a filter (SF) and a standard depth of 100 mm of substrate. The substrate was composed of 55% crushed brick, 30% pumice, 10% coir and 5% composted bark, a general mix used in the experiments of the Green Roof Centre of the University of Sheffield that does not use peat (Figure 5.2.1).

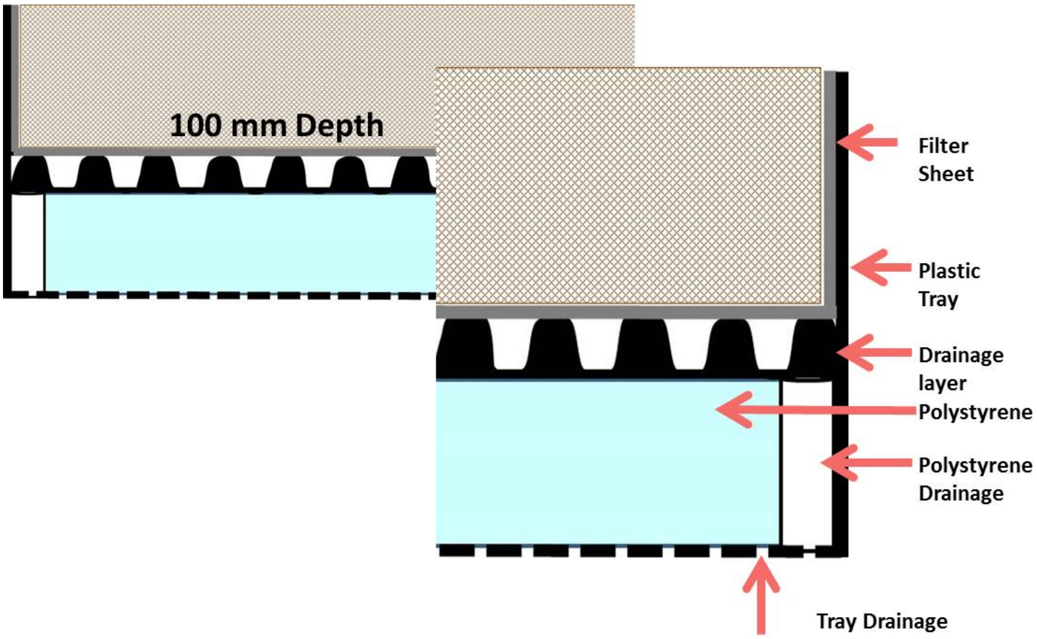


Figure 5.2.1 View of 100 mm substrate trays for experiments.

Each tray contained 1 plant of each species, with a total of 27 plants per tray in a grid of 7 by 4 and leaving one space, randomly selected, empty (Figure 5.2.2). Each screening unit had a total of six plants per species with a total of 168 plugs. Plants were spaced 100 mm from each other. The plants were arrayed randomly in each tray. Trays were watered on day 0, 3, 7, 11, and 15, and after day 15, weekly until water started to leak from the trays. This regime was followed during the first three months of establishment.

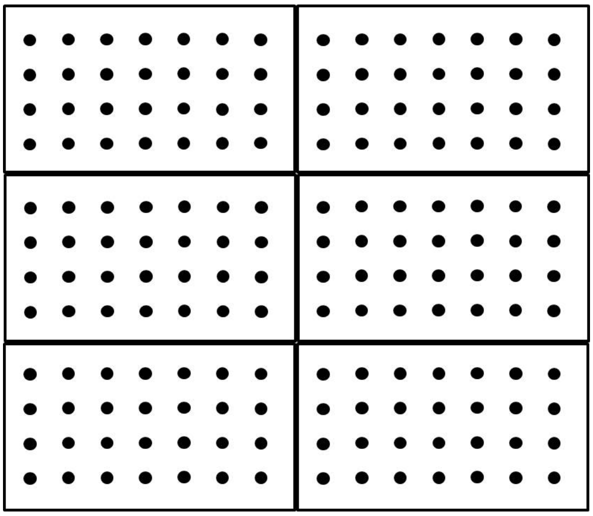


Figure 5.2.2 Set-up of experimental unit formed by 6 trays a 7 x 4 grid for plant.

After the first year of the screening, new plants of addition species and varieties were planted in the spaces left by the dead plants. Six plugs of rooted cuttings were planted in each screening unit. Trays were watered following the same pattern of the first year, on day 0,3,7,11 and 15 and after these weekly until water started to leak from the trays. On day 7, an NPK fertiliser 10:25:25 was applied to all trays, a second application was done on the third week and a last application on the third growing season. Weeding of the trays was performed regularly.

5.2.2 Selected species

During the initial stage of the screening, 22 species of the Crassulaceae family were tested as well as four different ecotypes sources of *Sedum moranense*. Unfortunately it was impossible to trace back the exact provenance of each of the *S. moranense* ecotypes, but as they presented major variations within the species, it was decided to test them. Two ecotypes of *Sedum confusum* were tested: one from *Cerro de la Yerba*, Chignahuapan, Puebla, and the second one from an unknown Mexican location. In this case, the two plants differed in size, since *Sedum confusum* from Cerro de la Yerba is much more compact and the leaf edges turn a characteristic reddish after prolonged exposure to sun.

In the second year, *Pachyphytum compactum, Sedum hultenii, S. palmeri* (two different ecotypes) and *S. palmeri* ssp. *rubromarginatum* were incorporated in to the screening. In the case of *S. palmeri*, it was also impossible to locate the provenance of two different forms, but it was decided to test both forms due to the differing shape and colour of the leaves of the species (Table 5.2.1). Three or possibly four hybrids (one is still waiting to be catalogued as a true species or hybrid) (Stephenson, 1994) were included in the screening for different reasons. The first, *Sedum* x *luteoviride,* was included because it is a naturally occurring wild hybrid between *Sedum greggii* and *Sedum dendroideum* ssp. *praealtum* found in Orizaba, in the state of Veracruz, Mexico (Evans, 1983, Stephenson, 1994). *Sedum* 'Rockery Challenger' is a hybrid between *Sedum mexicanum* x *S. sarmentosum,* a hybrid found in a garden in France (Stephenson, 1994), and it is included in this selection primarily to compare its performance with its parent *S. mexicanum*, especially in relation with survival during wet winters. *Sedum* ‘Spiral staircase’ is a new plant that it is also waiting to be catalogued either as a new Mexican species or as a natural hybrid between present Mexican species (Stephenson, 1994). Since it is a vigorous ground cover plant when grown at ground level, it was tested in the present study.

The last hybrid, x *Graptoveria* 'Acaulis,' is an unusual cross between two genera, probably between *Graptopetalum paraguayense* x *Echeveria amoena* (Bischofberger 2010). Since this hybrid was classified as hardy by Ray Stephenson (personal communication, 2010), and *Graptopetalum paraguayense* ssp. *bernalense* was already part of the screening this hybrid was included as it could be a useful comparison for hardiness of a ‘subspecies’ of the mother species. Unfortunately it was not possible to compare *Echeveria amoena* in to the screening because not enough plant material or reliable and verified provenance could be found.

Species used in screening in Cfb Climate: Sheffield, UK

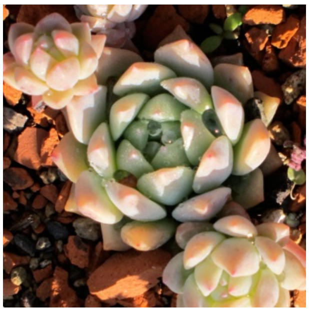
Species	Plant Form	Height	Foliage Colour	Flower Colour	Phys. Zone	Altitude	Vegetation Type
Echeveria agavoides	Rosette	3 to8 cm	Green	Salmon	MP	No data	Natural Grassland
Echeveria elegans	Rosette	3 to 10 cm	Pale glaucous blue green	Pale pink	TVB	Approx. 2500 m	*Pinus-Quercus* forest
Echeveria prolifica	Rosette	3 to 5 cm	Glaucous-green	Pale pink	TVB	No data	*Pinus-Quercus* forest
Echeveria secunda fa. *secunda*	Rosette	5 to 6.50 cm	Pale green	Yellow and red	TVB	3980 m	*Alpine and subalpine grassland*
Echeveria strictiflora	Rosette	7 to 9 cm	Glaucous green	Pale pink	SMO	no data	*Pinus-Quercus* forest
Graptopetalum paraguayense ssp. *bernalense*	Rosette	20 to 30 cm	Glaucous pink	White	SMO	700-800 m	No data
Pachyphytum compactum	Subshrub	10 to 20 cm	Glaucous green	Pinkish red	MP	2100 m	Natural grassland (mezquital)
Pachyphytum glutinicaule	Subshrub	15 to 25 cm	Glaucous green	Bright pink	MP	1550 m	Natural grassland (mezquital)
Pachyphytum werdermannii	Subshrub	10 cm	Glaucous greyish-piknish	Pale pink to bright pink	SMO	700 m	W. X. scrub -piedmont
Sedum australe	Subshrub	5 cm	Glaucous green	Yellow	No data	No data	No data
Sedum confusum "Cerro de la Yerba"	Subshrub	5 to 10 cm	Bright green	Yellow	TVB	No data	S. X. scrub (rosette)
Sedum confusum “Large Form”	Subshrub	20 cm	Bright green	Yellow	TVB	no data	No data
Sedum commixtum	Subshrub	20 to 30 cm	Glaucous bluish green	Greenish-yellow and red	NMSO	2600	*Alpine and subalpine grassland*
Sedum griseum	Subshrub	14-18 cm	Grey-green	White	TVB	Approx. 1800	*Pinus-Quercus* forest
Sedum hernandezii	Subshrub	14 cm	Bright green	Yellow	TVB	2400 m	*Quercus-Pinus* forest
Sedum hultenii	Subshrub	10 to 35 cm	Dark green	Yellow	SMO	1300 m	*Quercus-Pinus* forest
Sedum lucidum	Subshrub	10 to 15cm	Bright light green	Yellow	TVB	No data	*Quercus-Pinus* forest
Sedum mexicanum	Ground cover	6 to 8 cm	Bright green	Yellow	no data	No data	No data
Sedum moranense 138	Ground cover	5 to 10 cm	Dark green	White	TVB	2010 - 3060	*Quercus-Pinus* forest
Sedum moranense C4	Ground cover	5 to 10 cm	Dark green	White	no data	2010 - 3060	No data
Sedum moranense C7	Ground cover	5 to 10 cm	Dark green	White	no data	2010 - 3060	No data
Sedum moranense nursery	Ground cover	5 to 10 cm	Dark green	White	no data	2010 - 3060	No data
Sedum palmeri Clone *1*	Subshrub	15 to 20 cm	Light green	Yellow	no data	No data	No data
Sedum palmeri Clone *3*	Subshrub	15 to 20 cm	Light green	Yellow	no data	No data	No data
Sedum palmeri ssp. *rubromarginatum*	Subshrub	15 to 20 cm	Light pastel green	Yellow	MP	2100 m	S. X. scrub (sacrocaule)
Sedum dendroideum ssp. *praealtum*	Subshrub	30 to 50 cm	Bright light green	Yellow	SMO	No data	*Pinus-Quercus* forest
Sedum reptans	Ground cover	5 to 10 cm	Bright green	Yellow	MP	1700 m	*Quercus-Pinus* forest
Sedum stahlii	Subshrub	18 to 20 cm	Brown-red	Yellow	TVB	No data	S. X. scrub (rosette)

Sedum x 'Rockery challenger'	Subshrub	5 to 10 cm	Bright green	Yellow	non	No data	No data
Sedum x 'Spiral Staircase'	Ground cover	5 to 10 cm	Bright green	Yellow	non	No data	No data
Sedum x *luteoviride*	Subshrub	10 to 15	Bright green	Yellow	TVB	No data	*Pinus-Quercus* forest
x Graptoveria 'Acaulis'	Subshrub	10 to 20	Pale pinkish brown	Bright salmon	non	No data	No data

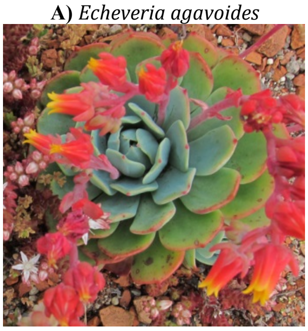
Table 5.2.1 List of Mexican Crassulaceae species used on screening for Cfb climate. (Eggli, 2003, Etter and Kristen, 1997, Evans, 1983, García-Morales, 2013, Hágsater et al., 2005, INEGI, 2011b, INEGI, 2011a, Meyrán-García, 2003, Pilbeam, 2008, Praeger, 1921, Stephenson, 1994). ***Non data*** **on the altitude column means it was not found of records in literature and first descriptions of the plant species.**

A) *Echeveria agavoides*

B) *Echeveria elegans*

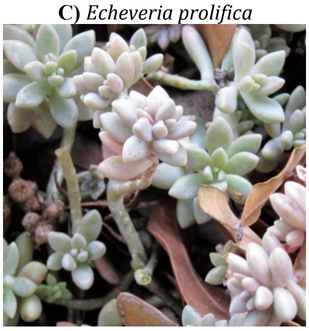


C) *Echeveria prolifica*



D) *Echeveria secunda* fa. *secunda*

E) *Echeveria strictiflora*



F) *Graptopetalum paraguayense* ssp. *bernalense*

G) *Pachyphytum compactum*

H) *Pachyphytum glutinicaule*

I) *Pachyphytum werdermannii*

J) *Sedum australe*

K) *Sedum confusum* "Cerro de la Yerba"

L) *Sedum confusum* “Large Form”

M) *Sedum commixtum*

N) *Sedum griseum*

O) *Sedum hernandezii*

P) *Sedum hultenii*

Q) *Sedum lucidum*

R) *Sedum mexicanum*

S) *Sedum moranense* C4

T) *Sedum moranense* C7

U) *Sedum moranense* C138

V) *Sedum moranense* Nursery **W)** *S. palmeri* ssp. *rubromarginatum* **X)** *Sedum dendroideum* ssp. *praealtum*

Y) *Sedum reptans* **Z)** *Sedum* x 'Spiral Staircase' **A1)** *Sedum* x 'Rockery challenger'

B1 *Sedum* x *luteoviride* **C1** X Graptoveria 'Acaulis'

Figure 5.2.3 Species used in the screening: A) *Echeveria agavoides,* B) *Echeveria elegans,* C) *Echeveria prolifica*, D) *Echeveria secunda* fa. *secunda,* E) *Echeveria strictiflora,* F) *Graptopetalum paraguayense* ssp. *bernalense,* G) *Pachyphytum compactum*, H) *Pachyphytum glutinicaule*, I) *Pachyphytum werdermannii,* J) *Sedum australe,* K) *Sedum confusum* "Cerro de la Yerba", L) *Sedum confusum* "Large Form", M) *Sedum commixtum*, N) *Sedum griseum* O) *Sedum hernandezii,* P) *Sedum hultenii,* Q) *Sedum lucidum,* R) *Sedum mexicanum,* S) *Sedum moranense* C4, T) *Sedum moranense* C7, U) *Sedum moranense* C138, V) *Sedum moranense* Nursery, W) *S. palmeri* ssp. *rubromarginatum*, X) *Sedum dendroideum* ssp. *praealtum*, Y) *Sedum reptans,* Z) *Sedum* x 'Spiral Staircase', A1) *Sedum* x 'Rockery challenger', B1) *Sedum* x *luteoviride,* C1) X Graptoveria 'Acaulis'

5.2.3 Data collection

Longest and shortest plant diameters, plant height, and individual survival were recorded on a monthly basis over the course of three growing seasons. In the flowering season, duration of flowering and the number of flowering plants were recorded. In the middle of third growing season plants were harvested. Above and below ground biomass were divided, the roots were washed and both shoots and roots were oven dried at 70° C for three days or more depending on weight stability. Root and shoot dry masses were then weight.

Data of ambient temperatures of the roof and the substrate of the trays were recorded weekly, and weekly data of precipitation was obtained from www.sheffieldweather.co.uk. Temperature of the substrate was measured using two 5TM Decagon probes and collected with an Em50 Decagon data logger. Each probe was positioned parallel to the substrate level in the middle of a tray at 50 mm depth. Measurements were recorded automatically each hour and the temperatures of the two probes were averaged.

5.2.4 Data analysis

The percentage survival for the repeated measures data was transformed with arcsine square root and analysed with a general linear model for repeated measures. For the cases in which the assumption of sphericity of the data was violated, a Greenhouse-Geisser correction for ($\varepsilon < 0.75$) or Huynd-Feldt ($\varepsilon > 0.75$) was applied and is specified on the results. Diameters, height and relative growth rate had a natural logarithm transformation and analysed with a linear model for repeated measures applied with package SPSS, and a Greenhouse-Geisser correction for ($\varepsilon < 0.75$) or Huynd-Feldt ($\varepsilon > 0.75$) were used in cases of violation of the sphericity assumption. The non-destructive relative growth rate (RGR) measurement was chosen as a proxy measurement of the growth of each plant relative to their initial size and was calculated using the following formula:

$$\mathrm{RGR} = [\mathrm{Ln}(\mathrm{Diameter\ 2}) - \mathrm{Ln}(\mathrm{Diameter1})]/t2 - t1 \quad \text{(Hunt, 1990)}$$

RGR = Relative growth rate
$\log_e$= Natural logarithm
Diameter 1= Initial mean diameter
Diameter 2= Subsequent diameter
t1= Initial time in days
t2= Subsequent time in days

A multivariate test was used to analyse the RGR dataset. All statistical tests had an alpha level of 0.05, and all graphs show the back transformed data or is stated otherwise.

The data set for the 5 taxa planted after the first year were analysed separately, following the same procedures described above.

5.2.5 Results

The results are presented in five sections. The first part of the results describes and analyses the temperature and precipitation data over the course of the screening. The second section presents the detailed results of each individual species arranged by performance: good performance, medium performance, and low performance and in subgroups of plants depending on their growing habit: ground cover species, subshrub species, and rosette species. The third section is the presentation of the combined overall results of the Mexican Crassulaceae survival, diameter relative growth rate, and diameter mean. The fourth section presents the results of the five additional plants that were incorporated into the screening during the second growing season. Finally the fifth section presents the percentage of flowering plants by species and reproduction and pollination responses.

5.2.5.1 Temperature and precipitation

This experiment was initiated in May 2011, and ran until July 2013. The precipitation data shows that the first year of the screening was particularly dry for Sheffield with no more than 85 mm per month. Between May 2011 and May 2012, the mean precipitation was 45.31 mm, and the total precipitation was 543.8 mm. The driest month was December, with only 11.8 mm, and the wettest month was January, with 84.8 mm (Figure **5.2.4** A). Between June 2012 and July 2013 the mean precipitation was 101.5 mm and the total precipitation was 1414.7 mm. The driest months were May and January, both with 51 mm, and the wettest month was December with 163.4 mm (Figure **5.2.4** A).

For the temperature data, only the air temperature was collected at the beginning of the screening, and from December 2011 it was possible for substrate temperature data to be collected as well (Figure **5.2.4** B). Over the course of the screening, the mean temperature differential between substrate and air was of 0.32 °C higher on the substrate (Figure **5.2.4** B). The mean minimum temperature differential between substrate and air, was 0.43 °C lower on the substrate (Figure **5.2.4** B). For the maximum temperatures, the average difference between substrate and air temperature was 5.8 °C. The maximum difference, in July 2013, was attained when the substrate temperature reached 49 °C -this is 19 °C higher than the air temperature at that time (Figure **5.2.4** B). These extremes in temperature attest to the extreme tolerance of the species tested in this study.

For the first year, May 2011 to May 2012, the mean annual air temperature was 10.5 °C, the mean highest temperature 20.15 °C, and the mean lowest temperature was 1.59 °C. The hottest month was July with a mean 15.1 °C, and the month with the lowest air temperature was February with a low -6.2 °C. From December 2011, when the substrate temperature record began, to May 2012, the mean substrate temperature was 5.2 °C, the mean minimum temperature -2.78 °C, and the mean maximum temperature was 17.6 °C. The hottest month was March with 29.7 °C but since the substrate data is not complete it is not possible to obtain the maximum substrate temperatures attained during the summer. The month with the lowest substrate temperature was February, with -5.2 °C, one degree higher than the air temperature at the time (Figure **5.2.4** B).

The second year of the screening from June 2012 until the end of the experiment in July 2013, the mean air temperature was 9.5 °C, the mean highest air temperature 18.77 °C, and the mean lowest air temperature was 1.77 °C. The month with the hottest day was July 2013, with 29.1 °C, and the month with the coolest day was January with -4.9 °C. The mean substrate temperature for this year was 10.1 °C. The mean highest substrate temperature was 25.7 °C, and the mean lowest substrate temperature was 1.5 °C. The month with the hottest substrate temperature was July 2013, with 48.7 °C. The month with the coolest substrate temperature was December, with -3.75 °C (Figure **5.2.4** B).

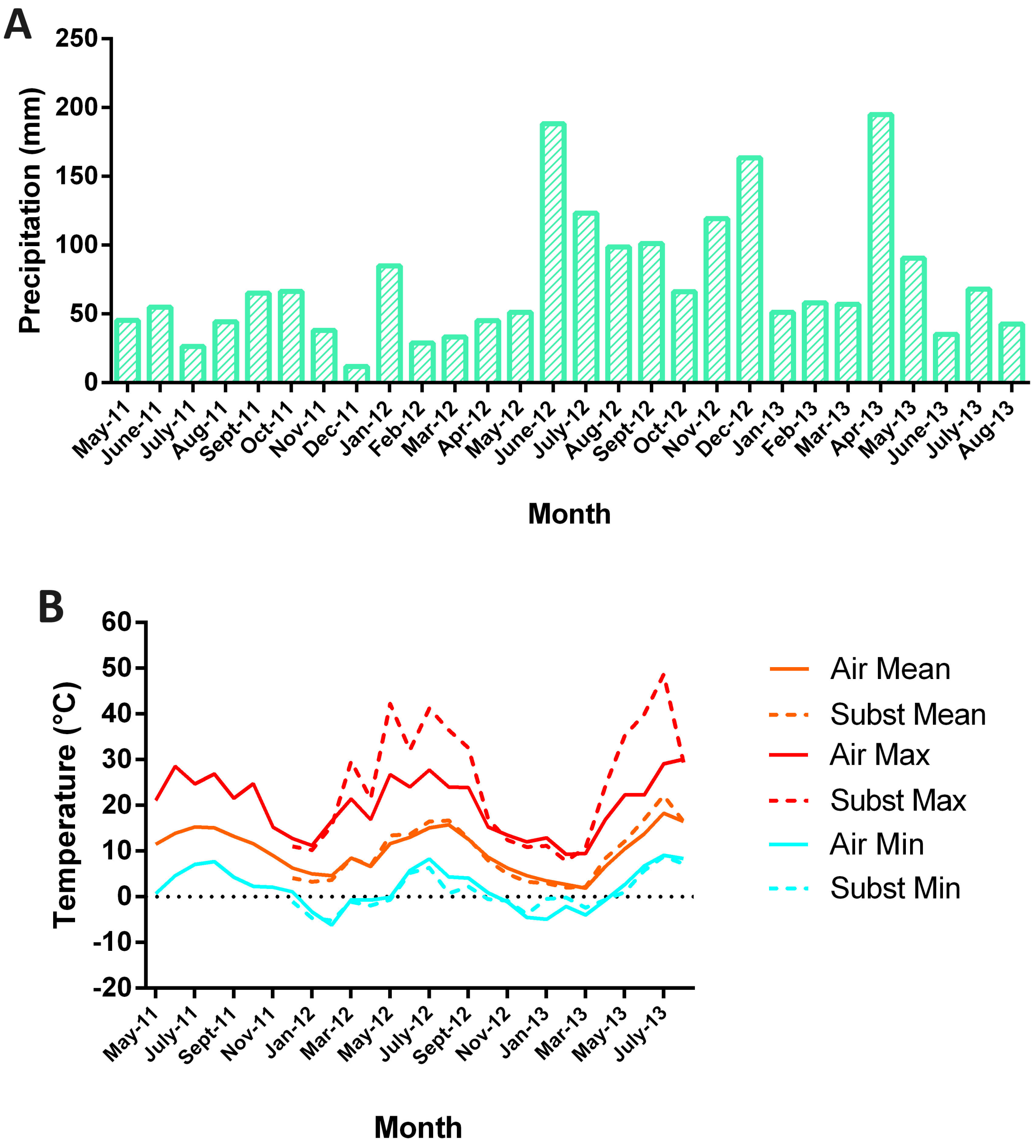


Figure 5.2.4 **A) Precipitation from May 2011 to August 2013 graph based on (Sheffield-Weather-Page, 2011a), Air temperatures for the city Sheffield from May 2011 to August 2013, and substrate temperature of experimental trays from Dec-2011 to Aug-2013. Based on (Sheffield-Weather-Page, 2011b) and data collected by 5TM Decagon probes and a Em50 Decagon data logger.**

5.2.5.2 Results per species

The results by species are presented in three groups according to their growth form: **ground cover** species, **subshrub** species and **rosette** species. Within each group, species are separated into three subgroups according to their overall performance on the roof during the screening: **high**, **medium** and **low** in accordance with their survival, response diameter RGR, mean diameter, height and number of flowers and duration of flowering.

Ground cover species

Ground cover species are short plants that can be used to provide the layer of vegetation closest to the ground. For the green roof systems these plants usually need to have a rapid growth rate at spread to prevent the invasion of opportunist weeds on the roof and to hold the substrate in place against winds. This type of plant is also used for their low weight, and because a great number of species with this growth habit can tolerate shallow substrates. As is evident below, the most successful groundcover plants were all varieties of single species: *Sedum moranense.* It is difficult to establish which *S. moranense* form had the best performance, but we will consider the individual survival rates and diameter growth as the main parameters.

High performance ground cover species

Sedum moranense 7

S. moranense 7 had a significantly higher ($p<0.05$) diameter RGR than all the rest of the species of the screening. The diameter RGR was never reduced after winters, and diameter had a constant and steady growth throughout the experiment (Figure 5.2.5). However, there were no significant changes over time in terms of height (Figure 5.2.5). This plant is one of the best ground cover species of the screening, since winter did not reduce its growth.

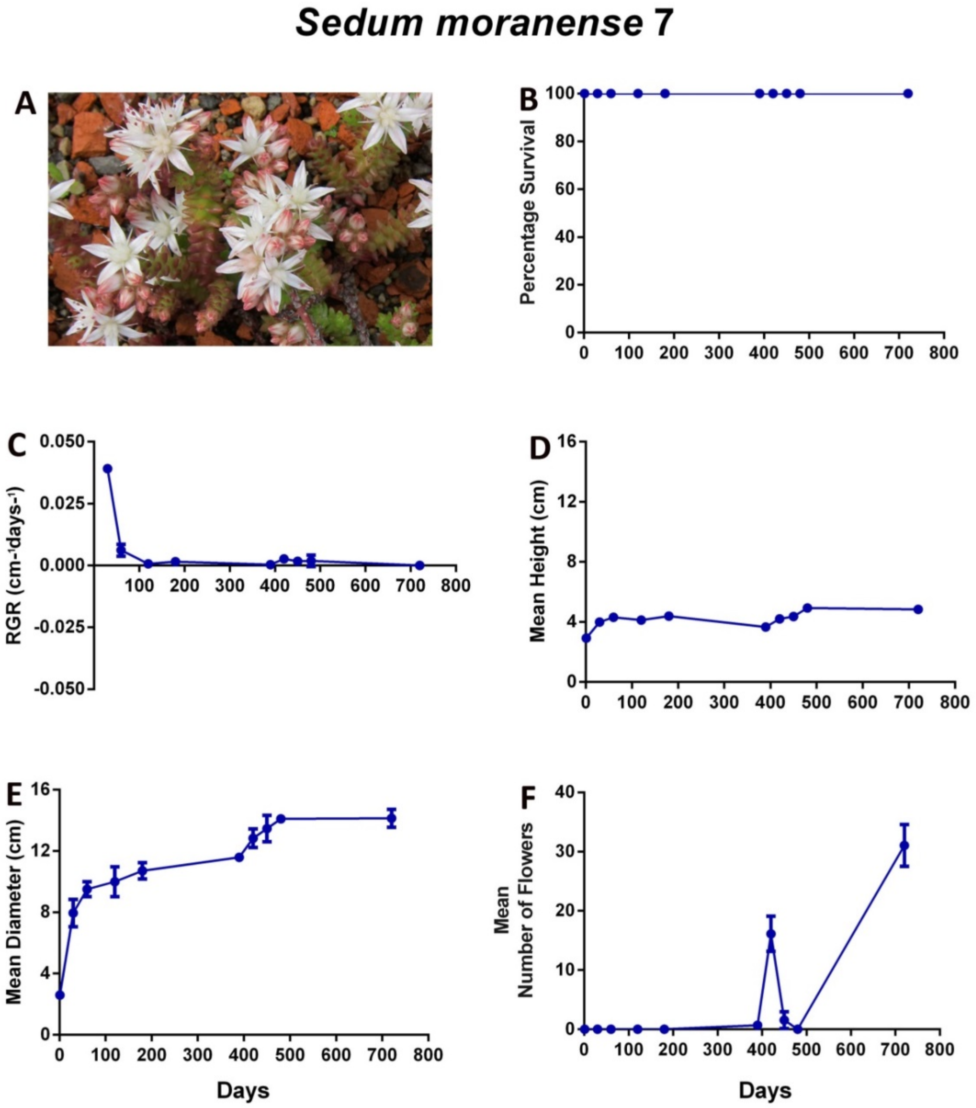


Figure 5.2.5 A) *Sedum moranense* 7, Repeated measures of: B) Percentage survival, C) Diameter Relative Growth Rate, D) Mean Height, E) Mean Diameter, F) Mean Number of Flowers. ±SEM bars only for between depths subjects. Negative RGR is due to reduction in size due to dehydration from cold damage.

Sedum moranense 138

Sedum moranense 138 had a 100 % survival (Figure 5.2.6 B). The diameter RGR was significantly (Tukey HSD, p< 0.05) higher than *Echeveria elegans, E. secunda, G. paraguayense* ssp. *bernalense, Pachyphytum werdermannii, Sedum confusum* Large Form, *S. confusum* Cerro de la Yerba, and *S. dendroideum* ssp. *praealtum.* The diameter of this species had a constant growth during the whole experiment, especially after the first winter (Figure 5.2.6 C and E). This species produced a great amount of flowers in the experiment, often visited by bees and bumblebees (Figure 5.2.6 F).

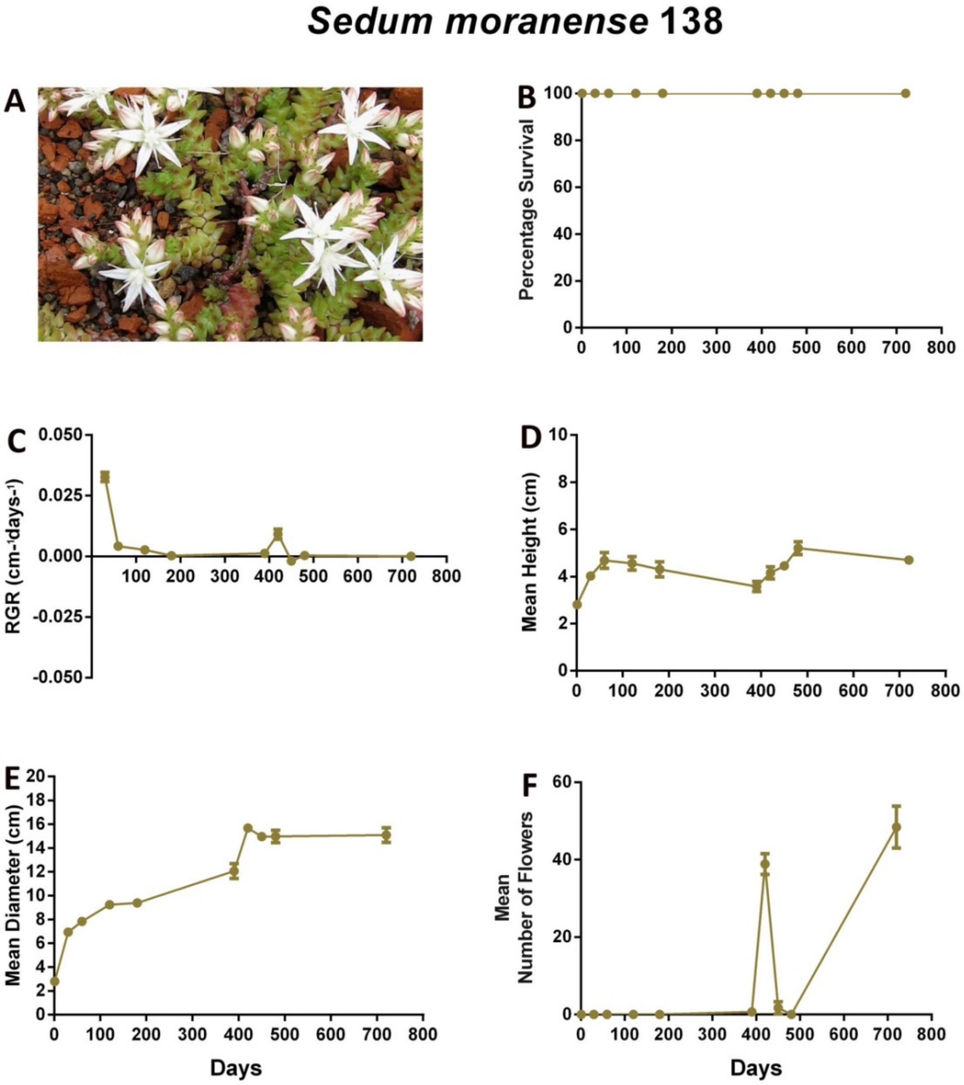


Figure 5.2.6 A) *Sedum moranense* 138, Repeated measures of: B) Percentage survival, C) Diameter Relative Growth Rate, D) Mean Height, E) Mean Diameter, F) Mean Number of Flowers. ±SEM bars only for between depths subjects. Negative RGR is due to reduction in size due to dehydration from cold damage.

Sedum moranense Nursery

Sedum moranense Nursery was sourced from a nursery, but according to its' similar features it could be a cross between *Sedum moranense* 7 and *Sedum moranense* 4. It had a 100 % survival (Figure 5.2.7 B). The diameter RGR was significantly higher (Tukey HSD, $p < 0.05$) than *Echeveria elegans*, *E. secunda, Graptopetalum paraguayense* ssp. *bernalense, Pachyphytum werdermannii, S. confusum* Large Form, *S. confusum* Cerro de la Yerba and *S. dendroideum* ssp. *praealtum.* The diameter had a steady growth throughout the year even after winters, and the mean height remained stable (between 4 and 6 cm) during the whole experiment (Figure 5.2.7 C and E). As with all the forms of *S. moranense* a high number of flowers were produced (Figure 5.2.7 F)

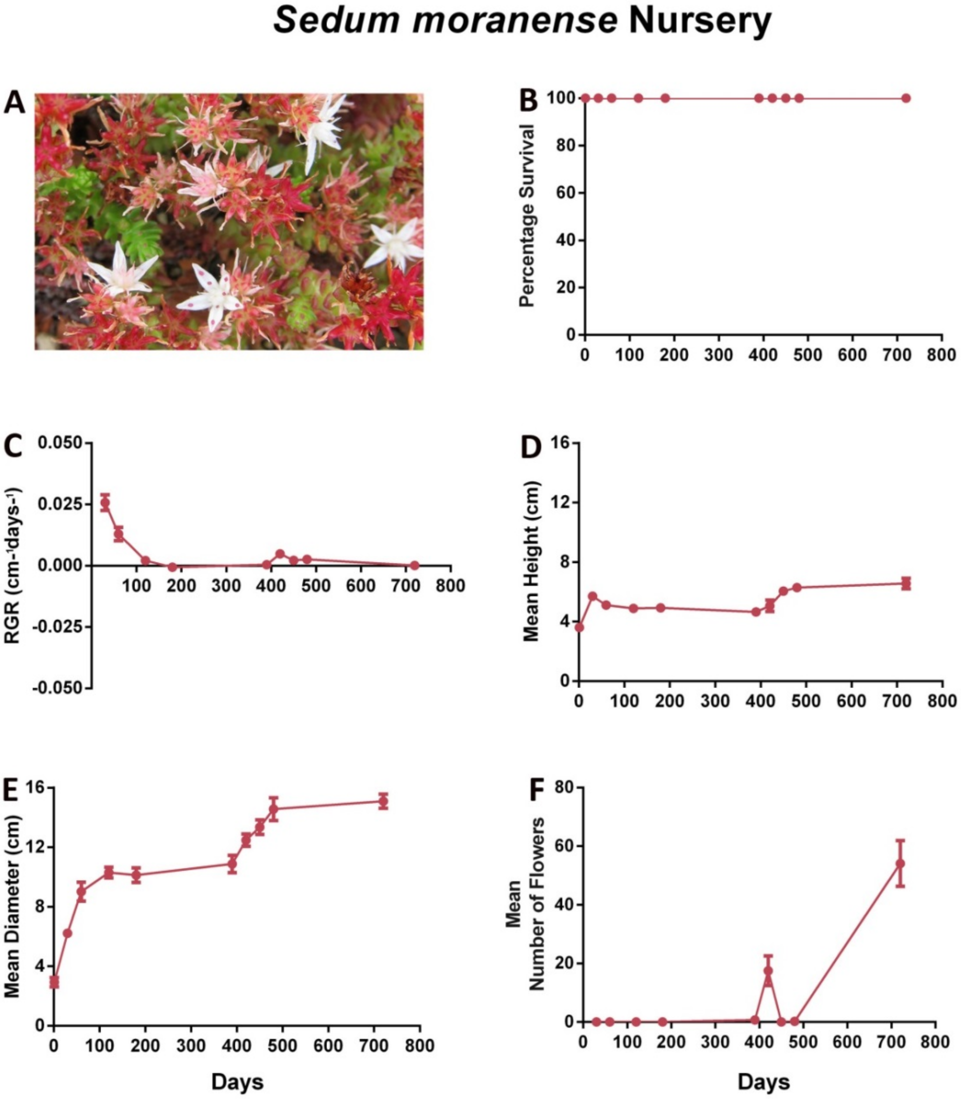


Figure 5.2.7 A) *Sedum moranense* Nursery, Repeated measures of: B) Percentage survival, C) Diameter Relative Growth Rate, D) Mean Height, E) Mean Diameter, F) Mean Number of Flowers. ±SEM bars only for between depths subjects. Negative RGR is due to reduction in size due to dehydration from cold damage.

Sedum moranense 4

S. moranense 4 had a 100 % survival (Figure 5.2.8 B), as for the rest of the forms of this species. This overall survival success could be attributed to the original provenance of this species, and all its varieties known to be able to grow at high altitudes on the snowy sides of volcanoes (Clausen, 1959). The diameter RGR of *S. moranense* 4 was significantly higher (Tukey HSD, p< 0.05) than most of the varieties and species, with the exception of *S. moranense* 7. *S. moranense* 4 was able to recover the diameter RGR after winter and to keep a steady diameter growth during most of the experiment, with the exception of the second winter when, probably due to the high amount of snow fall the plants reduced in size. Nevertheless, this reduction in diameter was not significant (Figure 5.2.8 E). Height was stable without significant changes, throughout the experiment (Figure 5.2.8 D). Interestingly, the flowering times for the other *S. moranense* varieties are very similar, but *S. moranense* 4, had not two but only one flowering season in the experiment. This could be because it was going to flower again, but later in the summer.

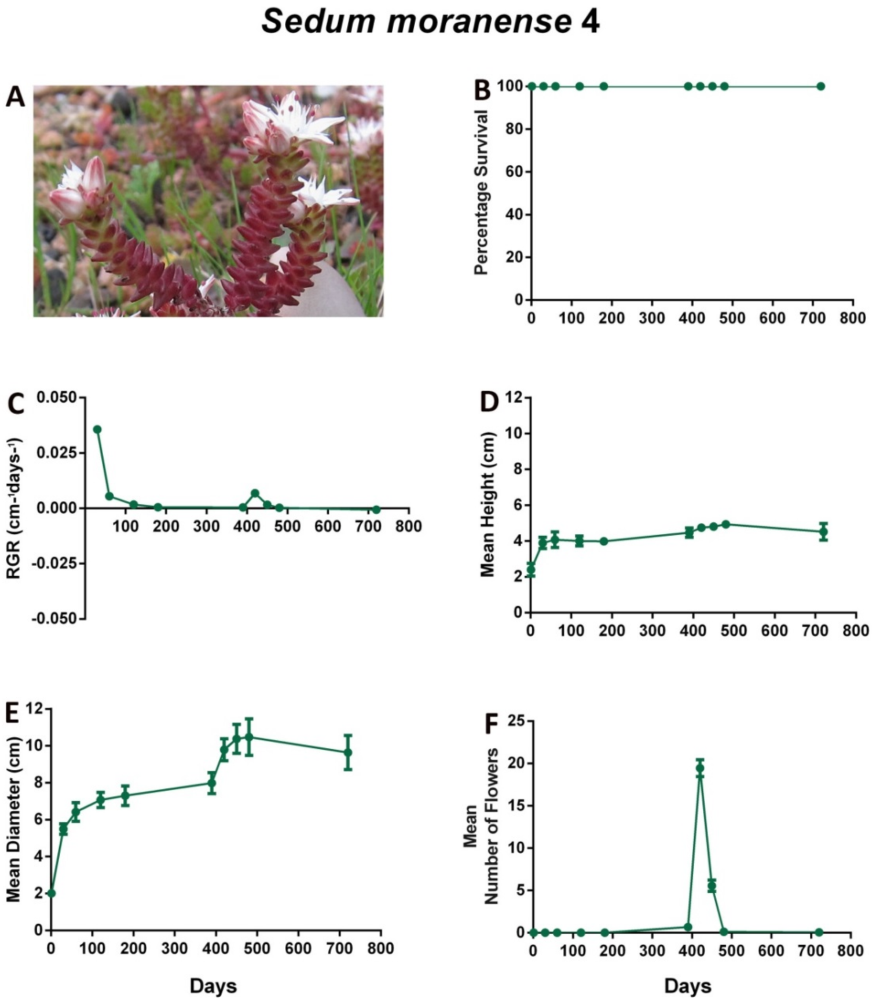


Figure 5.2.8 A) *Sedum moranense* 4, Repeated measures of: B) Percentage survival, C) Diameter Relative Growth Rate, D) Mean Height, E) Mean Diameter, F) Mean Number of Flowers. ±SEM bars only for between depths subjects. Negative RGR is due to reduction in size due to dehydration from cold damage.

Medium performance groundcover species

Sedum reptans

Sedum reptans suffer the death of several individuals after both winters, but especially during the second winter when there was more snowfall. However, the survival did not decrease below 60 % (Figure 5.2.9). The diameter RGR of *S. reptans* was significantly higher (Tukey HSD, $p<0.05$) than *E. elegans, E. secunda, Graptopetalum paraguayense* ssp. *bernalense, Pachyphytum werdermannii, S. confusum* Large Form and *S. praealtum*. The diameter presented reductions after the first and especially the second winter. This could also be related to the high amount of snowfall of the second winter, which this species does not experience in its native habitat (Figure 5.2.9 C and F). The height (between 2 and 4 cm) stayed stable during the whole experiment (Figure 5.2.9 D). Although this species did well before the second winter, the decrease in diameter after the second winter and the drop in survival does not make it a very reliable groundcover species for the unpredictable Cfb climate.

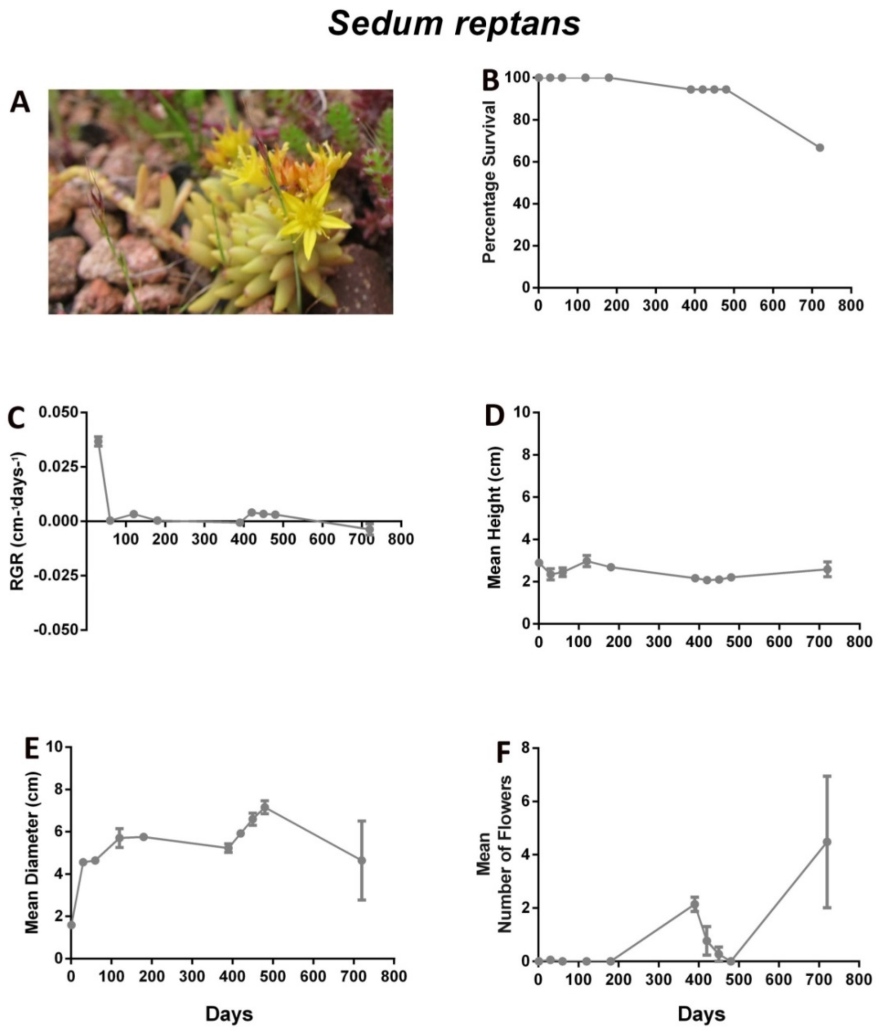


Figure 5.2.9 A) *Sedum reptans,* Repeated measures of: B) Percentage survival, C) Diameter Relative Growth Rate, D) Mean Height, E) Mean Diameter, F) Mean Number of Flowers. ±SEM bars only for between depths subjects. Negative RGR is due to reduction in size due to dehydration from cold damage.

Sedum 'Rockery Challenger'

This hybrid 'Rockery Challenger' had a 70 % survival by the end of the screening. The major mortality event was after the second winter. In comparison with one of its putative parent plants, *S. mexicanum*, 'Rockery Challenger' had a much better survival rate (Figure 5.2.10 B), perhaps due to 'hybrid vigour' or inherited characteristics of its other putative parent *S. sarmentosum*, from China and Japan. The diameter RGR was significantly higher (Tukey HSD, $p < 0.05$) than *Sedum confusum* Large Form. The diameters decreased after the two winters, nevertheless the diameters kept increasing after the second year (Figure 5.2.10 C and E). Height was stable (between 2 and 4 cm) during the whole experiment (Figure 5.2.10 D). This species does not have particular aesthetic characteristics and is very similar to European species like *Sedum reflexum* a species widely used as ground cover species for green roofs. In this regard, its inclusion in the study does not add greatly to the challenge of the expanding the plant palette.

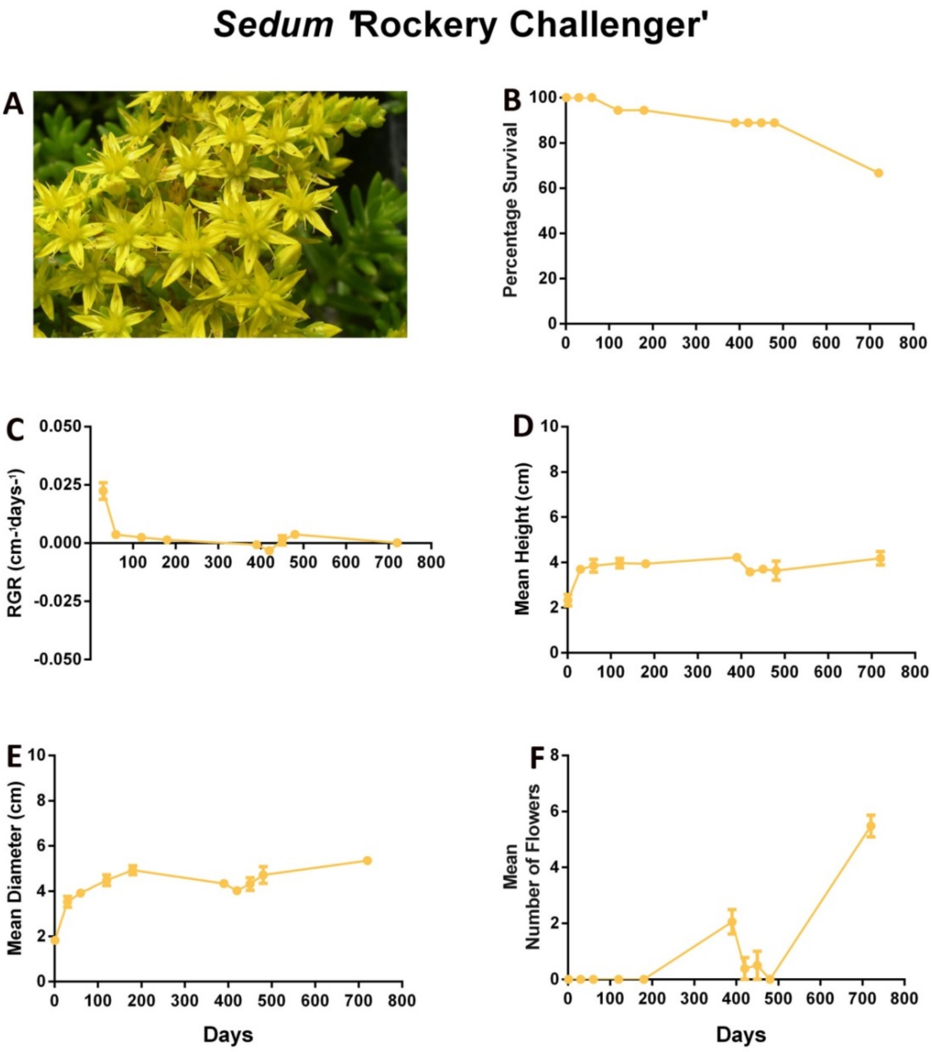


Figure 5.2.10 A) *S.* 'Rockery Challenger', Repeated measures of: B) Percentage survival, C) Diameter Relative Growth Rate, D) Mean Height, E) Mean Diameter, F) Mean Number of Flowers. ±SEM bars only for between depths subjects. Negative RGR is due to reduction in size due to dehydration from cold damage.

Low performance groundcover species

Sedum australe

S. australe was a poor performer during these harsh wet winters at Sheffield. It had a significant drop in survival ($p<0.05$) after the first winter with almost 50 % mortality (Figure 5.2.11 B). Due to the high diameter RGR during the first of the experiment months, *S. australe* had a significantly higher diameter RGR (Tukey HSD, $p< 0.05$) than *Echeveria elegans, E. secunda, Graptopetalum paraguayense* ssp. *bernalense, Pachyphytum werdermannii, Sedum confusum* Large Form, and *S. dendroideum* ssp. *praealtum*. Nevertheless, the low diameter and RGR displayed during the subsequent months strongly suggest that it would be a poor choice to use as a ground cover plant in Cfb climate (Figure 5.2.11 C). It did not present any significant changes in height and the number of flowers produced was always very low (Figure 5.2.11 D).

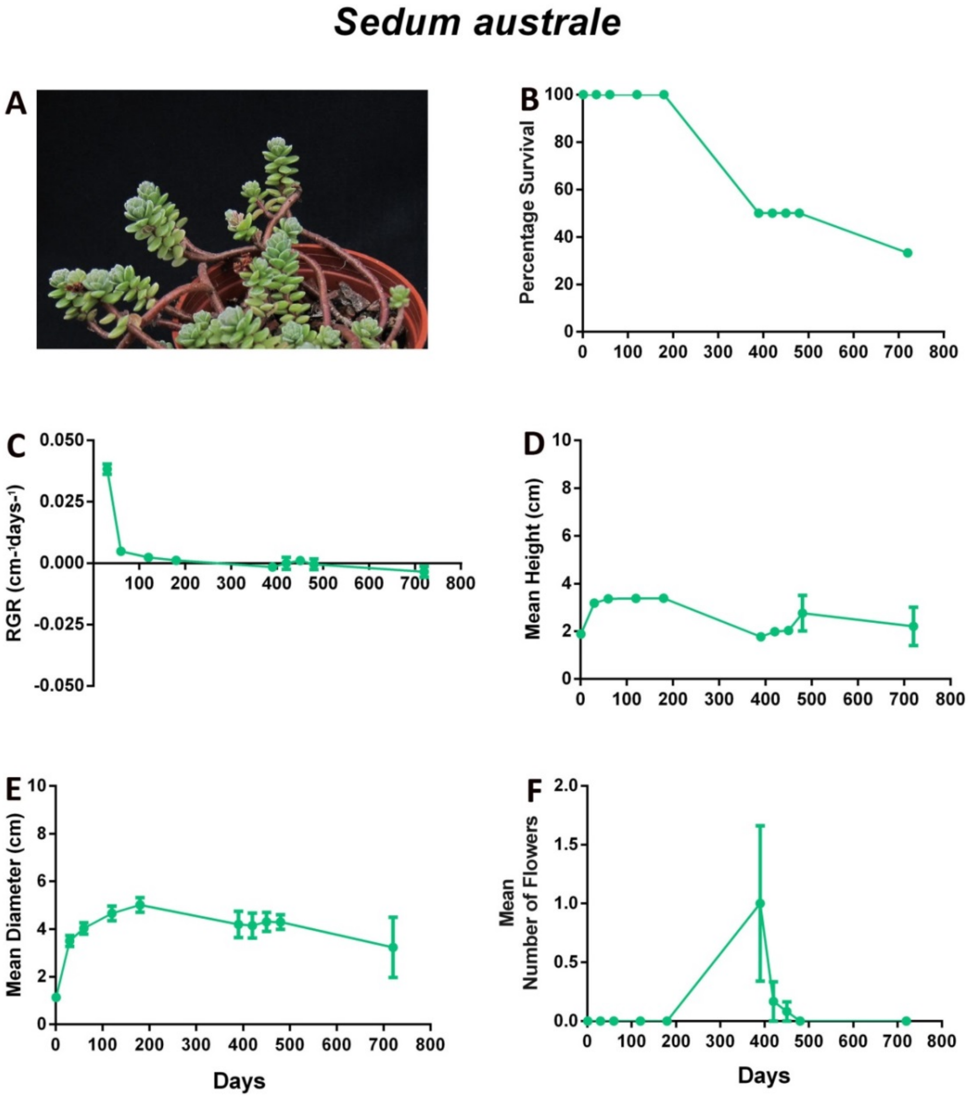


Figure 5.2.11 A) *Sedum australe,* Repeated measures of: B) Percentage survival, C) Diameter Relative Growth Rate, D) Mean Height, E) Mean Diameter, F) Mean Number of Flowers. ±SEM bars only for between depths subjects. Negative RGR is due to reduction in size due to dehydration from cold damage.

Sedum stahlii

S. stahlii (data not shown) had a very poor survival, with only 20% of plants remaining alive after the first winter. After the second winter all plants were dead. The RGR of this species was quite variable between plants, but it had a reduced mean RGR during the second growing season. Even though this species propagated very easily by leaves, the low survival, low diameter growth and low RGR do not make it suitable for the Cfb climate, since the plant cannot survive the wet winters. Clausen (1959) mentioned that the plants he first collected in Mexico were located in places with excessive drainage. If *S. stahlii* plants receive some water during the winter and the plants have optimal drainage then it may propagate well. However, this species is definitely not suitable to grow in wet soils during the cold season.

Sedum 'Spiral Staircase'

S. 'Spiral Staircase' (data not shown) had a poor survival, with a total mortality after the second winter. The rest of the performance indicators showed the same trend, since the plant was not able to recover its growth after the winters. Diameter RGR recovered a little after the first winter, but by the end of autumn the RGR reduced even more than after the first winter. The diameter grew constantly during the first growing season, but it never recovered after the first winter and the same pattern was observed with the height.

Sedum mexicanum

S. mexicanum also had a poor overall performance and will be a poor choice for a groundcover on a Cfb roof. It had a 0% survival by the end of the experiment. The first significant drop in survival ($p<0.05$) occurred in the spring after the first winter and, a year and a half later, all plants were dead. It did not present any significant changes in diameter relative growth rate (RGR), diameter or height during the whole experiment, and the three measurements had a constant reduction throughout the experiment.

Subshrub species

Subshrub sedum species do not have the same function as ground cover species. Instead they can be considered "accent" plants that form a second layer of vegetation on the roof, since they are taller than the ground cover species and not so compact. Nevertheless, these subshrub species which in their native habitat can grow up to 1 m, did not grow as tall on the roof in the Cfb climate. They are not forbs, their growth is much slower, they have succulent leaves and stems which can become woody. The subshrubs species of the screening considered include: *Sedum commixtum*, *S. confusum* 'Large Form', S. *confusum* 'Cerro de la Yerba', *S. griseum*, *S. hernandezii*, *S. lucidum*, *S. dendroideum* ssp. *praealtum* and *S*. x *luteoviride*.

High performance subshrub species

Sedum confusum 'Large Form'

S. confusum 'Large Form' had 100 % survival during the whole experiment (Figure 5.2.12 B). The diameter RGR was reduced after the first winter; nevertheless, the plants had a very good recovery. The RGR was not significantly higher than any other species; but it demonstrated a constant diameter growth even after the first winter (Figure 5.2.12 C). The height kept stable between 6 and 8 cm (Figure 5.2.12 D), in comparison with the 30 cm height that *S. confusum* 'Large Form' individuals can reach at ground level in their native habitat. The limited height achieved by this species could be explained by to the mechanical stress induced by the wind at the roof height, as seen in plants of *Pontentilla* and *Tobacco* (Anten et al., 2005, Liu et al., 2007), and/or by the lower temperatures it experience in the Cfb climate.

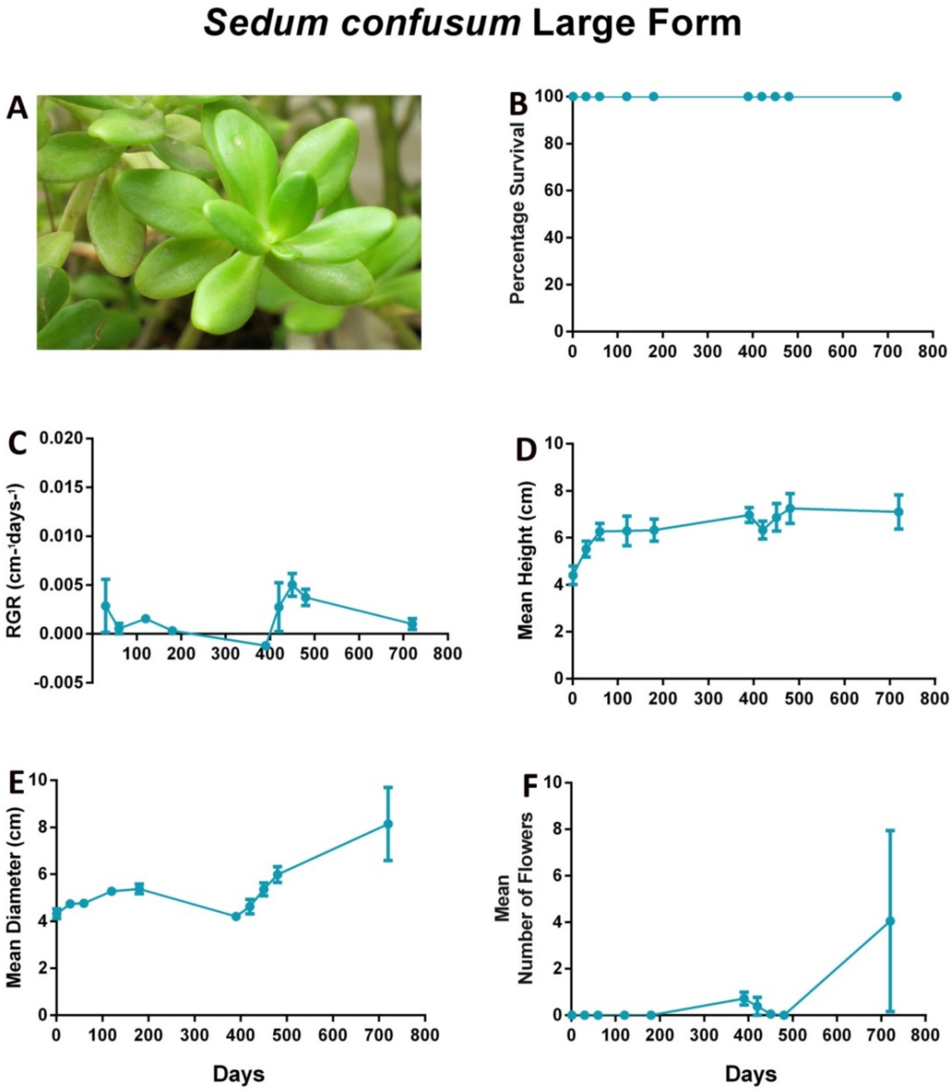


Figure 5.2.12 A) *Sedum confusum* 'Large Form', Repeated measures of: B) Percentage survival, C) Diameter Relative Growth Rate, D) Mean Height, E) Mean Diameter, F) Mean Number of Flowers. ±SEM bars only for between depths subjects. Negative RGR is due to reduction in size due to dehydration from cold damage.

Sedum confusum ‘Cerro de la Yerba’

S. confusum ‘Cerro de la Yerba’ has a smaller form than the above ‘Large Form’ the plant height and the leaves are both smaller, and the edges of the leaves become a rich red when exposed to strong sunlight. This plant had a 100 % survival (Figure 5.2.13 B). The diameter rate RGR was slightly reduced after the first winter, but during the second growing season it displayed its highest RGR (Figure 5.2.13 C). As until *S. confusum* Large Form, the RGR of this species was no better than any other species, but the diameter had a constant growth throughout the experiment (Figure 5.2.13 E). The height kept constant between 4 and 6 cm during the whole experiment (Figure 5.2.13 D), typical of its diminutive structure coupled with the response to the harsh roof environment.

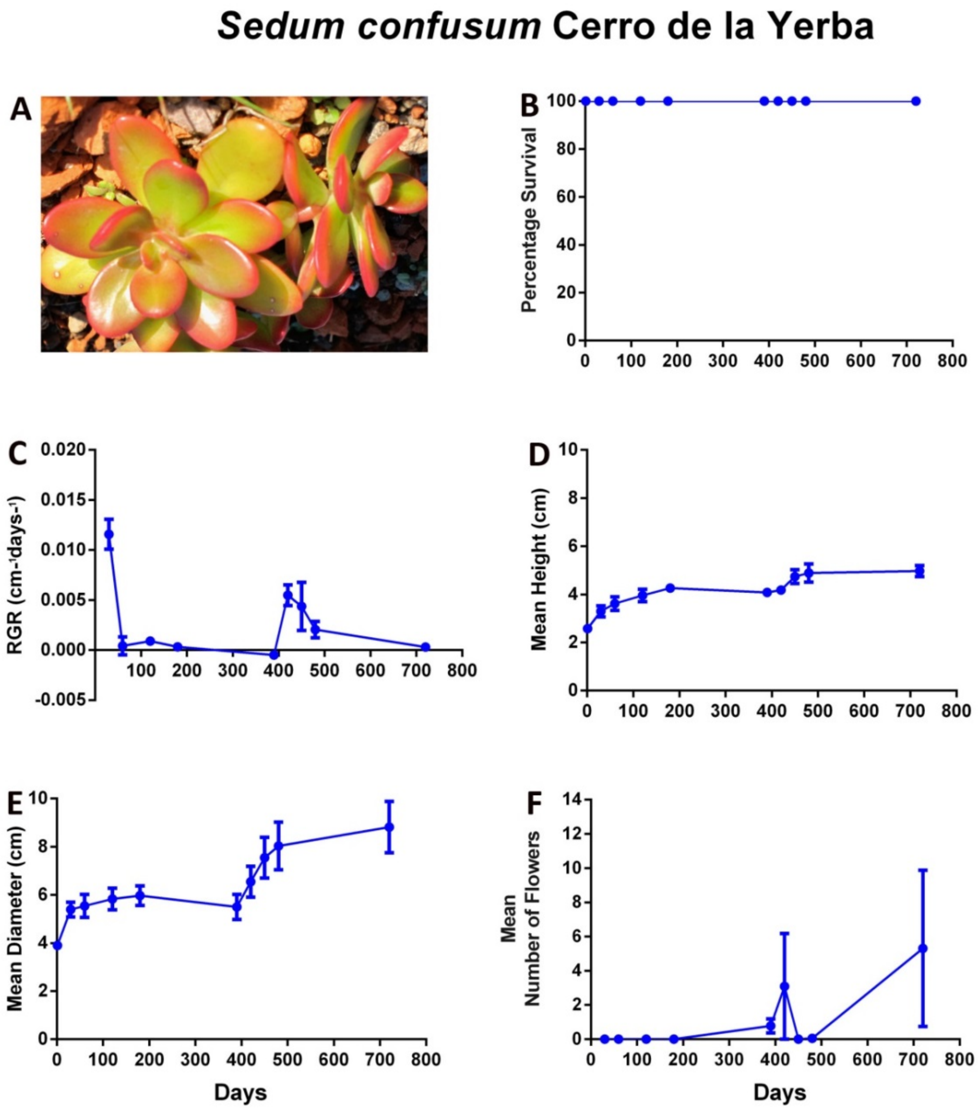


Figure 5.2.13 A) *Sedum confusum* Cerro de la Yerba, Repeated measures of: B) Percentage survival, C) Diameter Relative Growth Rate, D) Mean Height, E) Mean Diameter, F) Mean Number of Flowers. ±SEM bars only for between depths subjects. Negative RGR is due to reduction in size due to dehydration from cold damage.

Sedum dendroideum ssp. *prealtum*

S. dendroideum ssp. *prealtum* survival decreased after the first winter to 88 % but, after that its numbers remained steady (Figure 5.2.14 B) perhaps due to the established acclimation of survivors. The diameter RGR did not present any significant change at any time and was not significantly higher than any other species. Nevertheless, diameter growth increased a steadily increment throughout the year (Figure 5.2.14 C and E). The height of this subspecies can reach 1 meter on ground level, but in the roof environment the plant height reached, until the end of the experiment, no more than 12 cm (Figure 5.2.14 D). As with *S. confusum* Large Form, the wind's mechanical abrasion and 'burn' as well as low temperatures of Cfb climate might be the cause.

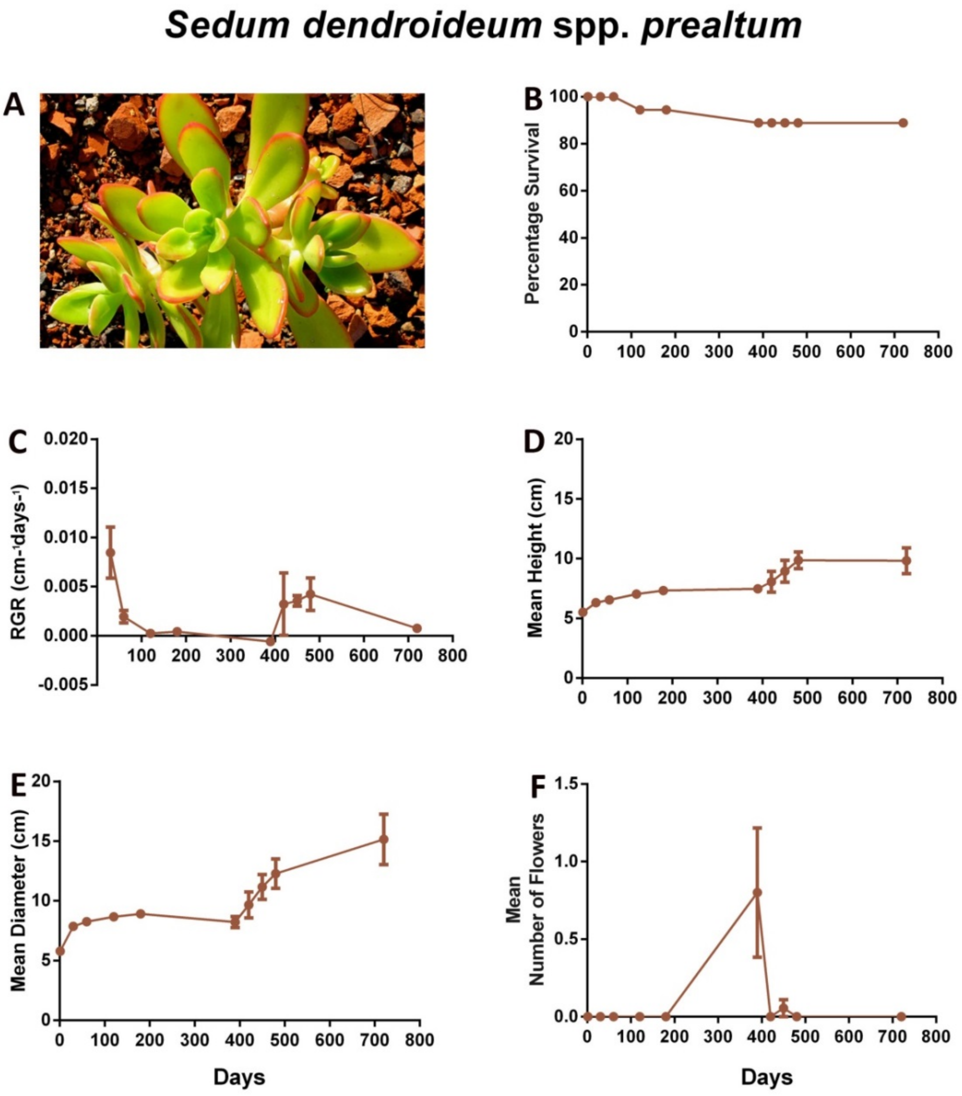


Figure 5.2.14 A) *Sedum dendroideum* spp. *praealtum,* Repeated measures of: B) Percentage survival, C) Diameter Relative Growth Rate, D) Mean Height, E) Mean Diameter, F) Mean Number of Flowers. ±SEM bars only for between depths subjects. Negative RGR is due to reduction in size due to dehydration from cold damage.

Sedum x *luteoviride*

The survival of *S.* x *luteoviride* had two small reductions after each winter with a final survival of 88% (Figure 5.2.15 B). The diameter RGR of this species was significantly higher than *Pachyphytum werdermannii* (Tukey HSD, $p< 0.05$) and it presented a good recovery after the first winter, although recovery was slow for several months after the harsher second winter. The diameter growth was a constant, with exception of the second winter where it decreased but not significantly (Figure 5.2.15 C and E). The height kept constant between 3 and 5 cm (Figure 5.2.15 D).

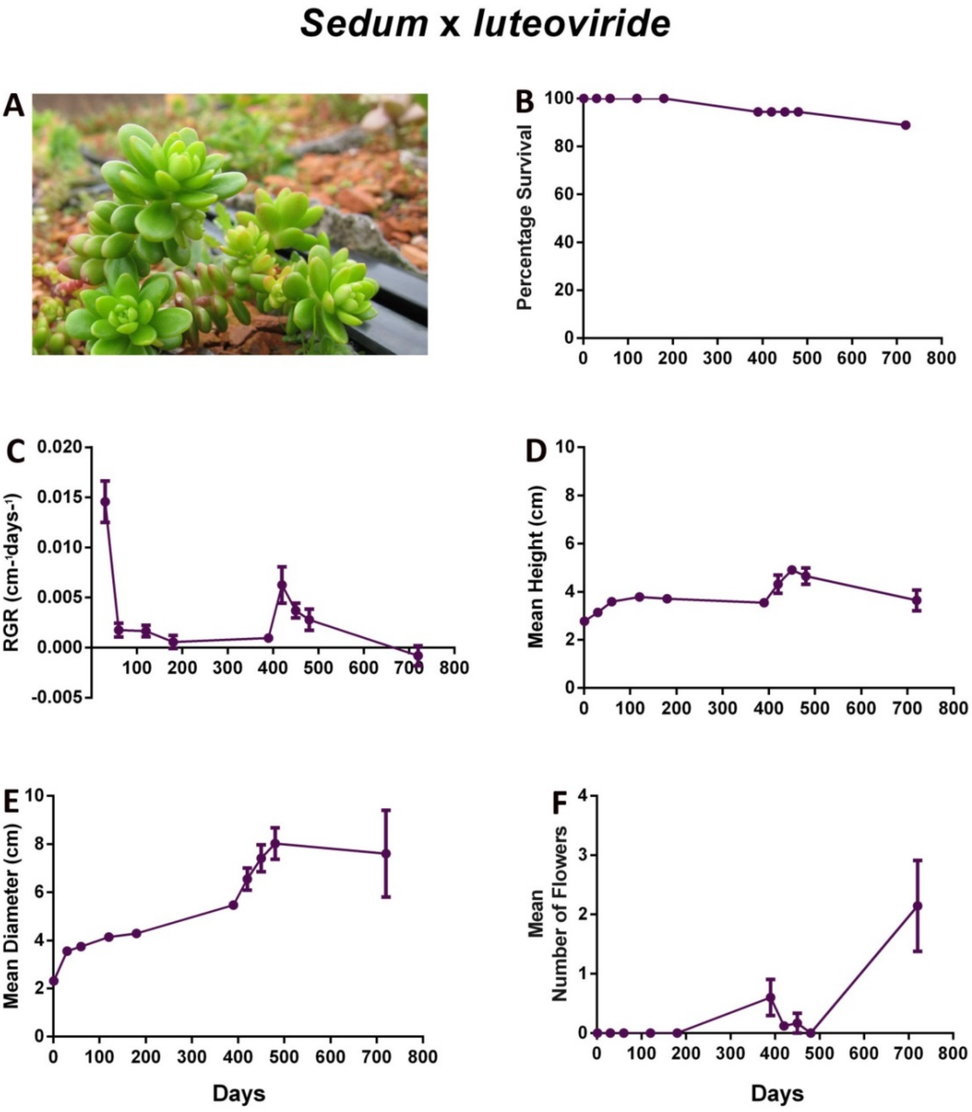


Figure 5.2.15 A) *Sedum* x *luteoviride,* Repeated measures of: B) Percentage survival, C) Diameter Relative Growth Rate, D) Mean Height, E) Mean Diameter, F) Mean Number of Flowers. ±SEM bars only for between depths subjects. Negative RGR is due to reduction in size due to dehydration from cold damage.

Sedum griseum

S. griseum had very poor survival, with 50 % survival after the first winter and only 20 % survival after the second. The diameter RGR never recovered significantly after the first winter (Figure 5.2.16 B and C). The diameter itself followed the same pattern, and although the height did improve after the first winter, the plants lost height again after the second winter (Figure 5.2.16 E and D). This die-back was probably caused by the high amount of snowfall experienced in the second year.

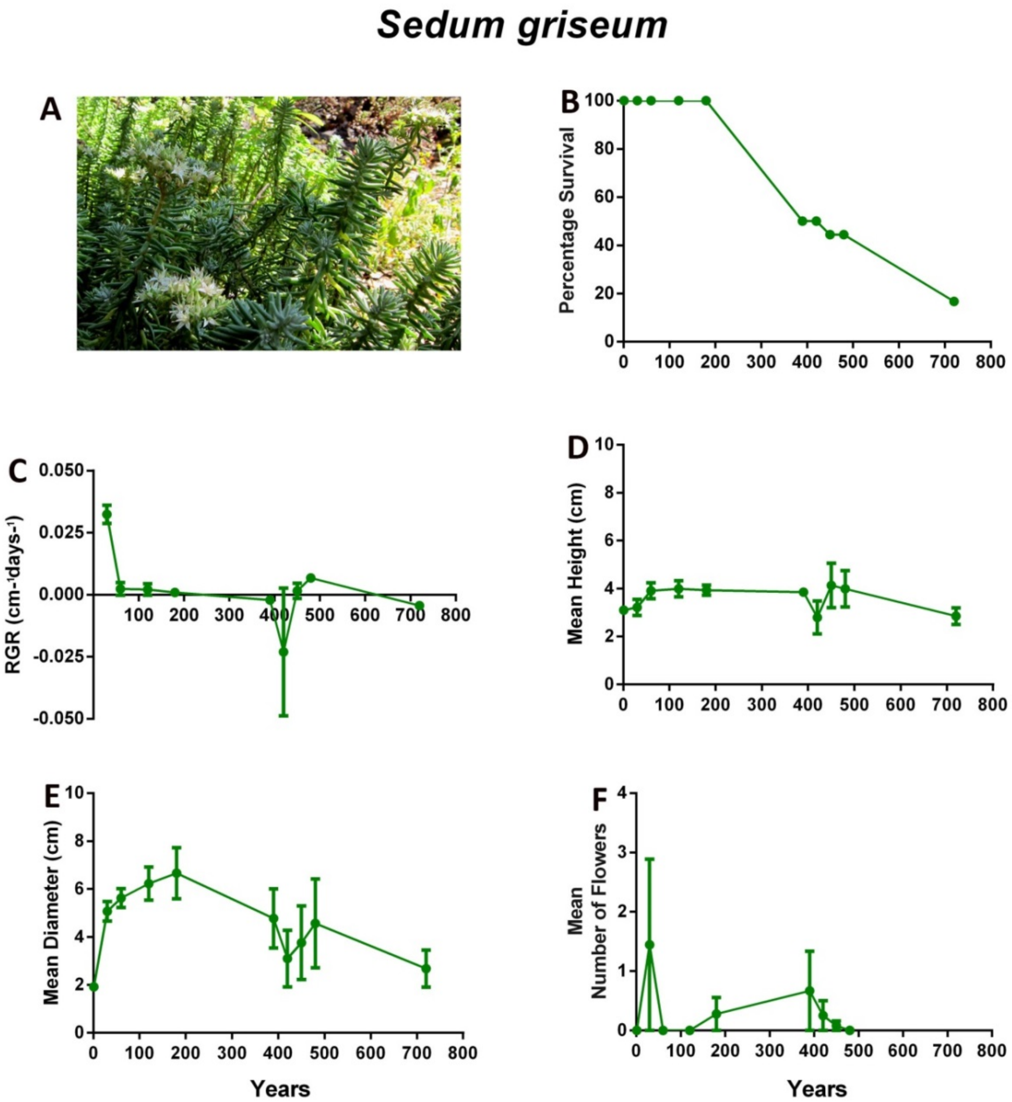


Figure 5.2.16 A) *Sedum griseum,* Repeated measures of: B) Percentage survival, C) Diameter Relative Growth Rate, D) Mean Height, E) Mean Diameter, F) Mean Number of Flowers. ±SEM bars only for between depths subjects. Negative RGR is due to reduction in size due to dehydration from cold damage.

Sedum commixtum

S. commixtum (data not shown) had a very poor survival and all the plants died rapidly during the first winter. Diameter RGR decreased rapidly with time during the first growing season, and diameter and height growth decreased steadily until the first winter when all plants died. This negative response strongly suggests that this species is incompatible with such extremely wet environment.

Sedum hernandezii

S. hernandezii (data not shown) had a similar performance to *S. commixtum,* but all the plants died finally after the second winter. The diameter RGR, was good while the plants were alive as was height increment and diameter increment. *S. hernandezii* grow very well during establishment, but as soon as the cold weather hit, the plants died and blackened rapidly.

Sedum lucidum

All the individuals of *S. lucidum* (data not shown) were dead after the second winter. The diameter RGR had some oscillations during the growing season, and diameter had a minor decrease during the autumn, but the plants kept growing until the onset of winter.

All four of these extremely poor performers, all with leaves of high water content, could not tolerate the frosts or snows. The lack of adaptation to temperatures below zero was evidenced by the characteristic blackening and rapid desiccation of tissues; damage from the intracellular and/or extracellular formation of ice crystals in the plant, which led to dehydration and/or the breaking up of cells when temperatures rose and the crystals melted away (Guy, 2003).

Rosette species

Rosette forming species are mostly found in the genera *Echeveria, Graptopetalum,* and *Pachyphytum.* The rosette plants are not ground cover species in the strict sense of the term and concept, since their slow grow does not permit the plant to cover a large amount of surface area in a rapid fashion. Nevertheless, the shapes, textures, colours and flowers can be integrated within communities of groundcover species, to provide important diversity to the green roof environment. The rosette species investigated in this experiment only had medium performance based on the criteria used, since they did not exhibit enough spread to ensure effective colonisation of the plots and substrate.

Medium performance rosette species

Echeveria secunda fa. secunda

E. secunda fa. *secunda* had 100% survival during the whole experiment (Figure 5.2.17 B). The diameter RGR was one of the lowest of all species, nevertheless the plant was able to recover after the winter (Figure 5.2.17 C). As with RGR, the diameters of the rosettes of this species did reduce after the winters, but the plants were able to recover (Figure 5.2.17 E). The decrease after the second winter was less than after the first winter. There was a constant increase in height, with some very minor and non-significant reductions, until the end of the experiment by which time it had reached a 4 cm mean in height (Figure 5.2.17 F).

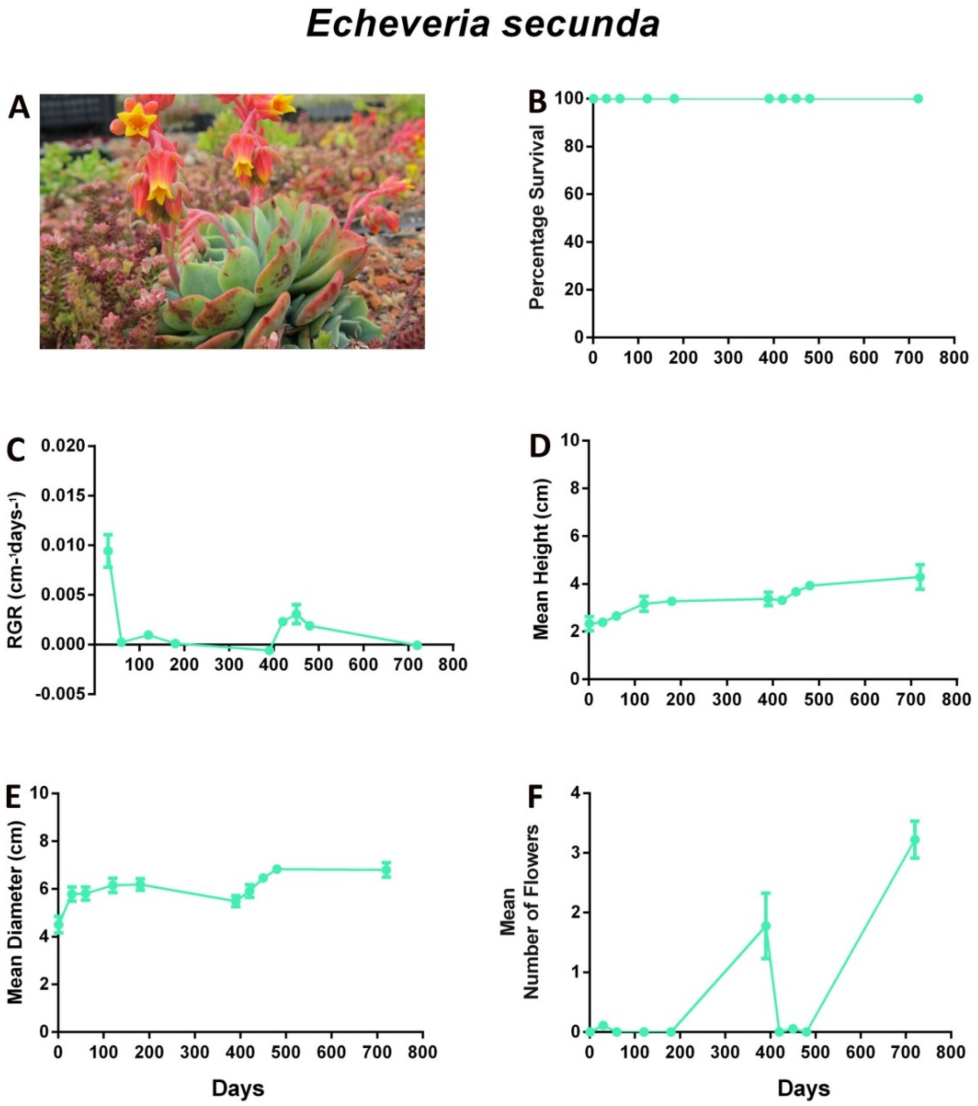


Figure 5.2.17 A) *E. secunda* fa.*secunda,* Repeated measures of: B) Percentage survival, C) Diameter Relative Growth Rate, D) Mean Height, E) Mean Diameter, F) Mean Number of Flowers. ±SEM bars only for between depths subjects. Negative RGR is due to reduction in size due to dehydration from cold damage.

During the experiment *E. secunda* was one of the most aesthetically appealing species, since it could recover its healthy appearance in a short period of time after winter and its flowers (although small) are very colourful. The good performance of this form of *Echeveria secunda* might have be attributed to the climate of its provenance, where the plants can experience snow several times during the year (Pilbeam, 2008). A high number of bees and bumblebees such as *Bombus lapidarius* visited the abundant flowers.

Echeveria elegans

E. elegans experienced some mortality after the winters, with 61% survival of individuals by the end of the experiment (Figure 5.2.18). The diameter RGR of this species was low but it was able to recover after the winters (Figure 5.2.18). Nevertheless diameter growth was reduced after the first winter, and it did not improve much afterwards (Figure 5.2.18). A close observation of the rosettes showed that some plants that grew plantlets on the sides become detached from the substrate, and the roots were not able to anchor properly. Nevertheless, in another roof, in which the same species was planted as par of a demonstration, the plants did not experience this effect. It would, therefore be advisable to observe what causes the up-rooting of the plants from the substrate; it could be the effect of the wind or the inquisitive action of birds picking up the plants. During this experiment numerous crows and other corvids where observed disturbing the substrate, perhaps in search of invertebrates and at times considerable damage was done to some plants because of this.

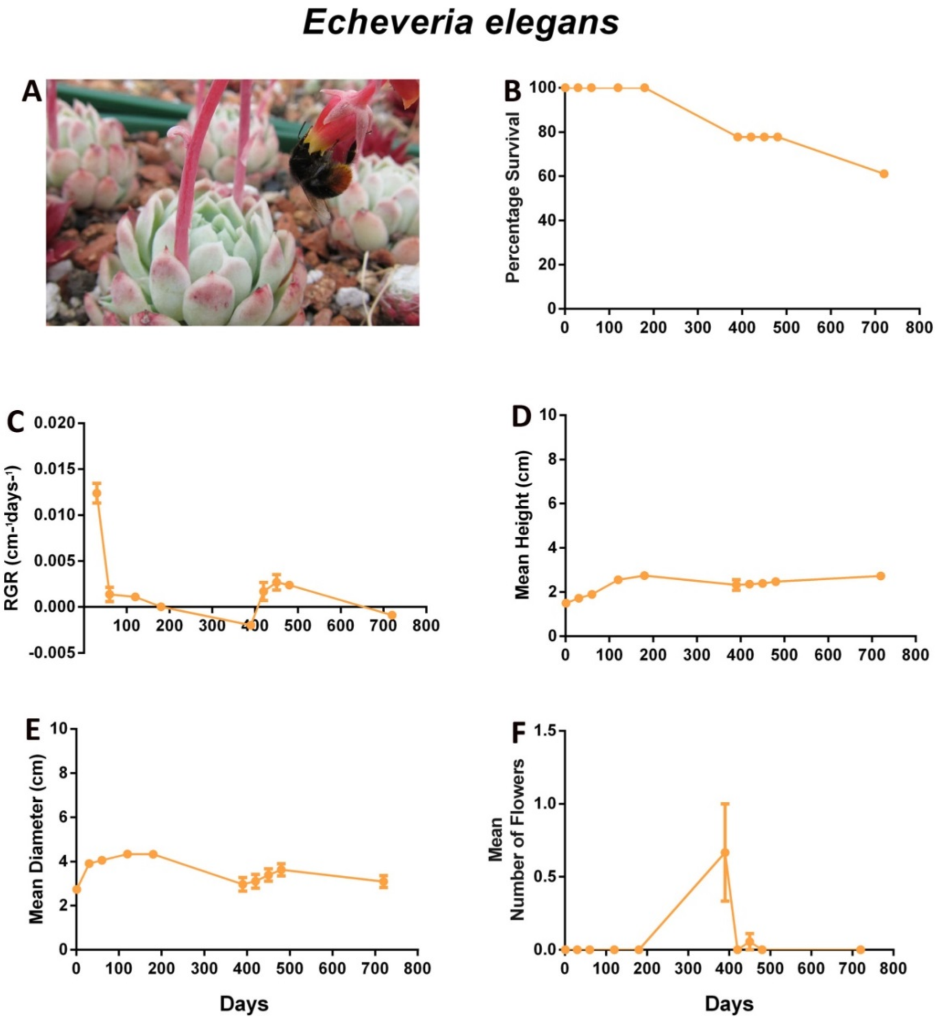


Figure 5.2.18 A) *E. elegans,* Repeated measures of: B) Percentage survival, C) Diameter Relative Growth Rate, D) Mean Height, E) Mean Diameter, F) Mean Number of Flowers. ±SEM bars only for between depths subjects. Negative RGR is due to reduction in size due to dehydration from cold damage.

X *Graptoveria ‘Acaulis’*

This hybrid X *Graptoveria* ‘Acaulis’ had a final survival of 77% (Figure 5.2.19 B), and it performed much better than *Graptopetalum paraguayense* ssp. *bernalense*, which (as described in the next section) is not necessary one of the mother plants of this species. There is currently no location data for *Graptopetalum paraguayense* ssp. *paraguayense,* which is usually attributed as the mother plant of the hybrid, but the species must be native to a nearby area (Eggli, 2003, Kimnach Myron, 1986). The diameter RGR of X *Graptoveria* ‘Acaulis’ was significantly higher than *Graptopetalum paraguayense* ssp. *paraguayense* (perhaps indicative of ‘hybrid vigour’), *Pachyphytum werdermannii* and *Sedum confusum* Large Form (Tukey HSD, $p < 0.05$) (Figure 5.2.19 C). Diameter presented a steady increase with very low reductions in diameter after the winters. Height had a constant growth throughout the screening (Figure 5.2.19 D).

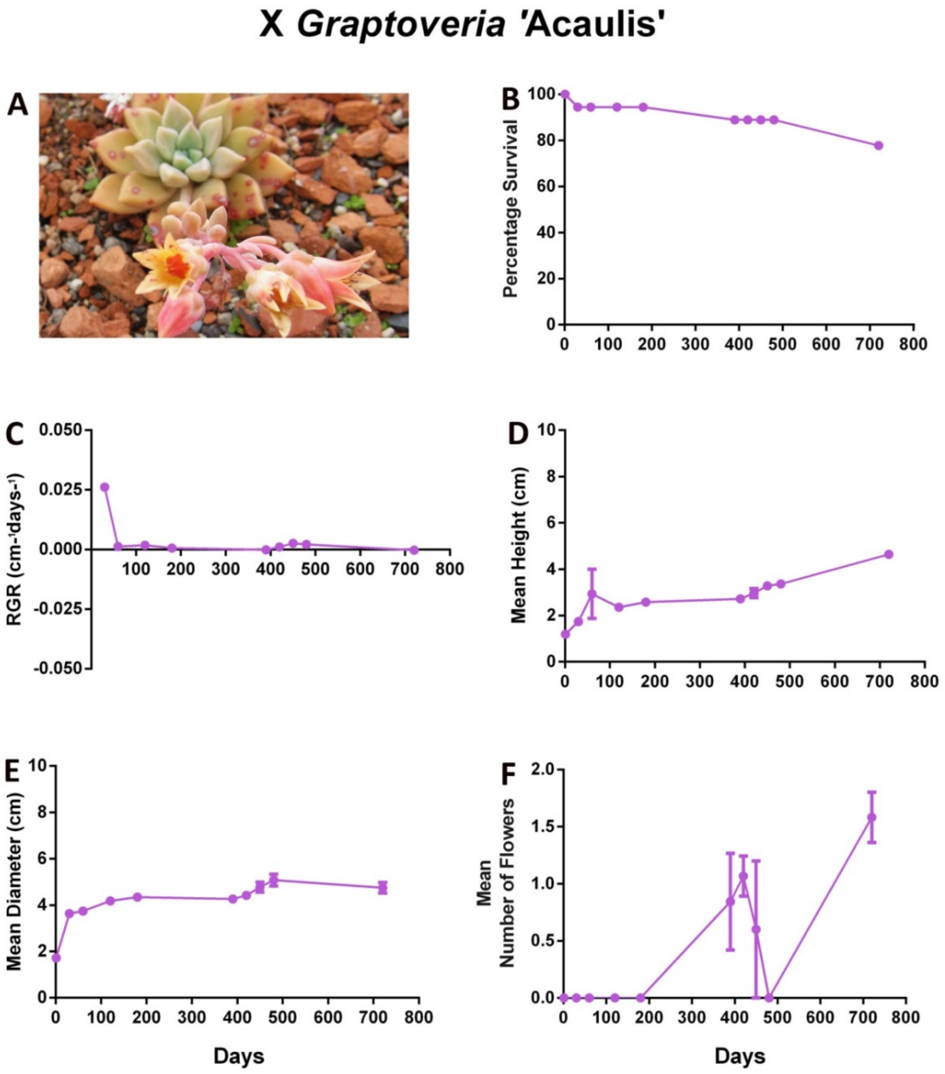


Figure 5.2.19 A) X *Graptoveria* ‘Acaulis’, Repeated measures of: B) Percentage survival, C) Diameter Relative Growth Rate, D) Mean Height, E) Mean Diameter, F) Mean Number of Flowers. ±SEM bars only for between depths subjects. Negative RGR is due to reduction in size due to dehydration from cold damage.

Low performance rosette species

Pachyphytum werdermanii

The survival of *P. werdermanii* (data not shown) decreased after each successive winter, but by the end of the experiment this species still had an 80% survival. The diameter RGR however, was never able to recuperate after the first winter. This drop in RGR could be explained by the dramatic change of leaf form in to shorter and wider more stunted, shape by the dehydration effect of the wind stres, as is seen in leaves of *Plantago major* subjected to wind stress (Anten et al., 2010). Diameter was reduced after both winters, although not significantly, and height kept constant between 3 and 5 cm.

Graptopetalum paraguayense ssp. *bernalense*

The survival of *Graptopetalum paraguayense* ssp. *bernalense* (data not shown) had a massive decrease on 60% after the first winter and decreased down to 33% survival after the second winter. The diameter RGR was very low during the first year, but had a high improvement during the second growing season. Diameter had a decrease after the first winter, it grew steadily and recuperated by the second winter.

Echeveria agavoides

The survival of *Echeveria agavoides* (data not shown) was very low, with only 22 % of individuals surviving to the end of the screening. Most of the individuals died during the first winter. The diameter RGR and diameter of the surviving plants of *E. agavoides* decreased after the first winter, but was able to recover, only to get reduced once more after the second winter.

Pachyphytum glutinicaule

P. glutinicaule (data not shown) had a very poor performance, the survival dropped drastically, especially after the first winter. The diameter RGR decreased greatly after the first winter, probably because of the loss of the biggest and most mature leaves during the winter. Nevertheless, the RGR improved before the second winter, but dropped once more after the second winter.

Echeveria strictiflora

E. strictiflora had a 50 % survival after the first winter, but by the end of the second winter all plants were dead, with evidence of fungal diseases. When trees and plants are exposed to freezing temperatures, ice crystal formation leads to a shrinking and cracks in the epidermis (Guy, 2003), which may lead to fungi and pathogens entering the plant. The diameter RGR, decreased after the first winter, but was able to recover however diameter did not reach the size of the first growing season after the first winter.

Echeveria prolifica

Most of the *E. prolifica* plants died after the first winter, and only one plant survived but died after the second winter. The RGR dropped steeply after the first winter, and the only plant that survived had an oscillation between growth and shrinking.

5.2.5.3 Overall percentage survival, diameter RGR, diameter and height models

Percentage survival

The overall percentage survival data for May 2011 to July 2013 for the overall model was significantly different between days and between days and species ($p<0.001$, Greenhouse-Geisser correction). The major challenges of survival for the Mexican species in climate Cfb are the low temperatures of the winter combined with high precipitation, a combination not often experienced in their habitats. Therefore, a closer look at the winter temperatures and precipitation data can shed some light on the survival patterns. The 2011-2012 winter had a higher mean temperature than the 2012-13 winter (Table 5.2.2Figure 5.2.19). The mean minimum air temperature was lowest for the 2012-13 winter; nevertheless the substrate of the 2011-2012 reached lower temperatures (Table 5.2.5.1). The mean maximum temperatures of both air and substrate were higher during the 2011-12 winter (Table 5.2.2). Total precipitation was higher during the winter 2012-2013, with double the rainfall of the previous year (Table 5.2.2).

Year	Mean Temperature		Minimum Temperature		Maximum Temperature		Precipitation
	Substrate	Air	Substrate	Air	Substrate	Air	
Winter 2011-2012	4.91 °C	6.1 °C	-3.00 °C	-2.25 °C	16.65 °C	15.50 °C	158.60 mm
Winter 2012-2013	2.61 °C	3.17 °C	-1.67 °C	-3.87 °C	10.16 °C	10.92 °C	329.60 mm

Table 5.2.2 Mean, Minimum and Maximum temperatures and total precipitation of Winter 2011-12 and 2012-13 in °C and mm.

Most of the species with survival rates lower than 20 % had their major mortality event during the 2011-12 winter, including, *Sedum commixtum, S. hernandezii* and *S. lucidum.* The total mortality of these species showed that they are not able to tolerate any sub zero temperature if combined with high precipitation. Nevertheless, species like *Echeveria strictiflora*, X *Graptoveria* 'Acaulis', *S.* 'Rockery Challenger' and *S. reptans* had a major mortality event during the winter of 2012-13. These species were able to withstand a cooler substrate during the first winter when it was comparatively drier, but some of the plants were unable to survive the combination of a lower air temperature (-1.62 °C) and double the precipitation (171 mm).

Diameter relative growth rate

There was a wide range of RGR across the species tested (Figure 5.2.20). The overall model for the diameter repeated measures was highly significant ($p<0.001$, Greenhouse-Geisser correction). The diameter (RGR) for the repeated measures of the screening was also highly significant for the overall model ($p<0.001$, Greenhouse-Geisser correction). In all cases, the first measurement of the RGR was the highest. Species *Sedum moranense* 7 had a significantly higher mean diameter RGR ($p<0.05$) than *Echeveria elegans*, *E. secunda*, *G. paraguayense* ssp. *bernalense*, X *Graptoveria* 'Acaulis', *Pachyphytum werdermannii*, *S. confusum* "Large Form", *S. confusum* "Cerro de la Yerba", *S. dendroideum* ssp. *praealtum*, *S.* 'Rockery Challenger' and *S.* x *luteoviride* (Figure 5.2.20). *S. moranense* 4 had a significantly higher mean diameter RGR ($p<0.05$) than all the same set if species named above, except for *Graptoveria* 'Acaulis' (Figure 5.2.20). *S. moranense* Nursery and *S. moranense* 138 both displayed significantly higher mean diameter RGR ($p<0.05$) as with *Sedum moranense* 7, with the exception of X *Graptoveria* 'Acaulis', *S.* 'Rockery Challenger' and *S.* x *luteoviride* (Figure 5.2.20

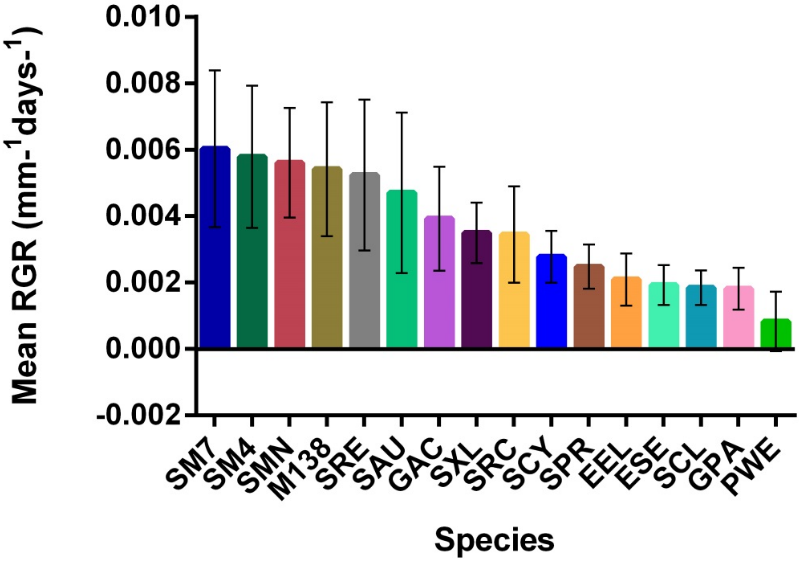


Figure 5.2.20 Mean relative growth rate with ±SEM for species with all cases: *S. moranense* 7 (SM7), *S. moranense* 4 (SM4), *S. moranense* Nursery (SMN), *S. moranense* 138 (M138), *S. reptans* (SRE), *S. australe* (SAU), X *Graptoveria* 'Aucalis' (GAC), *S.* x *luteoviride* (SXL), *S.* "Rockery Challenger" (SRC), *S. confusum* "Cerro de la Yerba" (SCY), *S. dendroideum* ssp. *praealtum* (SPR), *Echeveria elegans* (EEL), *Echeveria secunda* (ESE), *S. confusum* "Large Form" (SCL), *Graptopetalum paraguayense* ssp. bernalense (GPA), *Pachyphytum werdermannii* (PWE). Negative RGR is due to reduction in size due to dehydration from cold damage.

Sedum reptans had a significantly higher mean diameter RGR ($p<0.05$) than *Echeveria elegans*, *E. secunda*, *Graptopetalum paraguayense* ssp. *bernalense*, *Pachyphytum werdermannii*, *S. confusum* 'Large Form', *S. confusum* 'Cerro de la Yerba' and *S. dendroideum* spp. *praealtum* (Figure 5.2.20). *S. australe* displayed significantly higher mean diameter RGR ($p<0.05$) than *E. elegans, E. secunda, Graptopetalum paraguayense* ssp. *bernalense, Pachyphytum werdermannii, S. confusum* 'Large Form' and *S. dendroideum* ssp. *praealtum* (Figure 5.2.20). X *Graptoveria*

'Acaulis' had significantly higher mean diameter RGR ($p<0.05$) than *Graptopetalum paraguayense* ssp. *bernalense*, *Pachyphytum werdermannii*, and *S. confusum* 'Large Form' (Figure 5.2.20) *S.* x *luteoviride* has significantly higher mean diameter RGR than *Pachyphytum werdermannii*, and *S.* "Rockery Challenger" has a significantly higher RGR than *S. confusum* 'Large Form', both with ($p<0.05$) (Figure 5.2.20).

Diameter, height and total biomass

The plant diameters, as with the survival, was strongly affected by the onset and duration of winter. In some cases, plants that shrunk or died back during the winter period were able to re-establish themselves during the following growing season, like both forms of *S. confusum* and *S. dendroideum* ssp. *praealtum*. However other species, although remaining alive never achieved more growth , like in the case of both *Pachyphytum* species and *S. griseum*. Height data showed that some of the species that grow from 50 cm to 1 m in Mexico at ground level, like *S. dendroideum* ssp. *praealtum,* had a much reduced height at the roof level in Sheffield, nevertheless short groundcover species remain the same. The final total biomass between the species used in the screening was significantly different ($p< 0.05$) (Figure 5.2.21). *S. dendroideum* ssp. *praealtum,* being the biggest species of all the screening had the highest biomass. This reflects the size of the plant, and that it had one of the highest diameter RGR. *S. moranense* Nursery was the *S. moranense* variety that had the highest biomass, although *S. moranense* 7 had the highest diameter RGR.

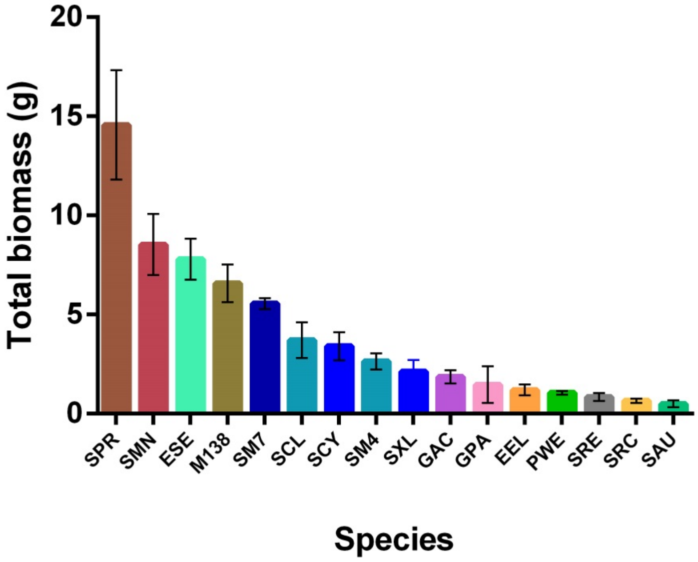


Figure 5.2.21 Total biomass with ±SEM for: *S. dendroideum* ssp. *praealtum* (SPR), *S. moranense* Nursery (SMN), *Echeveria secunda* (ESE), *S. moranense* 138 (M138), *S. moranense* 7 (SM7), *S. confusum* "Large Form" (SCL), *S. confusum* "Cerro de la Yerba" (SCY), *S. moranense* Clone 4 (SM4), *S.* x *luteoviride* (SXL), X *Graptoveria* 'Acaulis' (GAC), *Graptopetalum paraguayense* ssp. *bernalense* (GPA), *Echeveria elegans* (EEL), *Pachyphytum werdermannii* (PWE), *S. reptans* (SRE), *S.* "Rockery Challenger" (SRC), *S. australe* (SAU).

Nevertheless, all plants of this species had the greatest total biomass within the screening. *E. secunda*, achieved a very high total biomass as well, but this species had one of the lowest RGR, which suggest that probably this plant grows more in the thickness of its tissue than in diameter.

5.2.5.4 Second year screening species

After the first winter, the total mortality of some of the species resulted in empty spaces. Therefore 5 plants of *Pachyphytum compactum, Sedum hultenii,* two *Sedum palmeri* varieties of different provenances and *Sedum palmeri* ssp. *rubromarginatum,* were incorporated in to the screening. The data for these additional species includes the second growing season, second winter and the first measurement of the third growing season. *Pachyphytum compactum* has a rosette form, while all the additional *Sedum* species are classed as subshrubs.

Subshrub species

Sedum palmeri 3

Sedum palmeri 3 had a 73% final survival. The first plants died not because of cold or wet but because birds picked at them and broke them repeatedly during the first growing season. Therefore mortality due to the winter was only 13 %. The diameter RGR was negative during the whole experiment, and this might be due to reduction in size by wind dehydration as well as the special interest of birds (Figure 5.2.22 B and C). Diameter and height means were also negative in both cases (Figure 5.2.22 E and D).

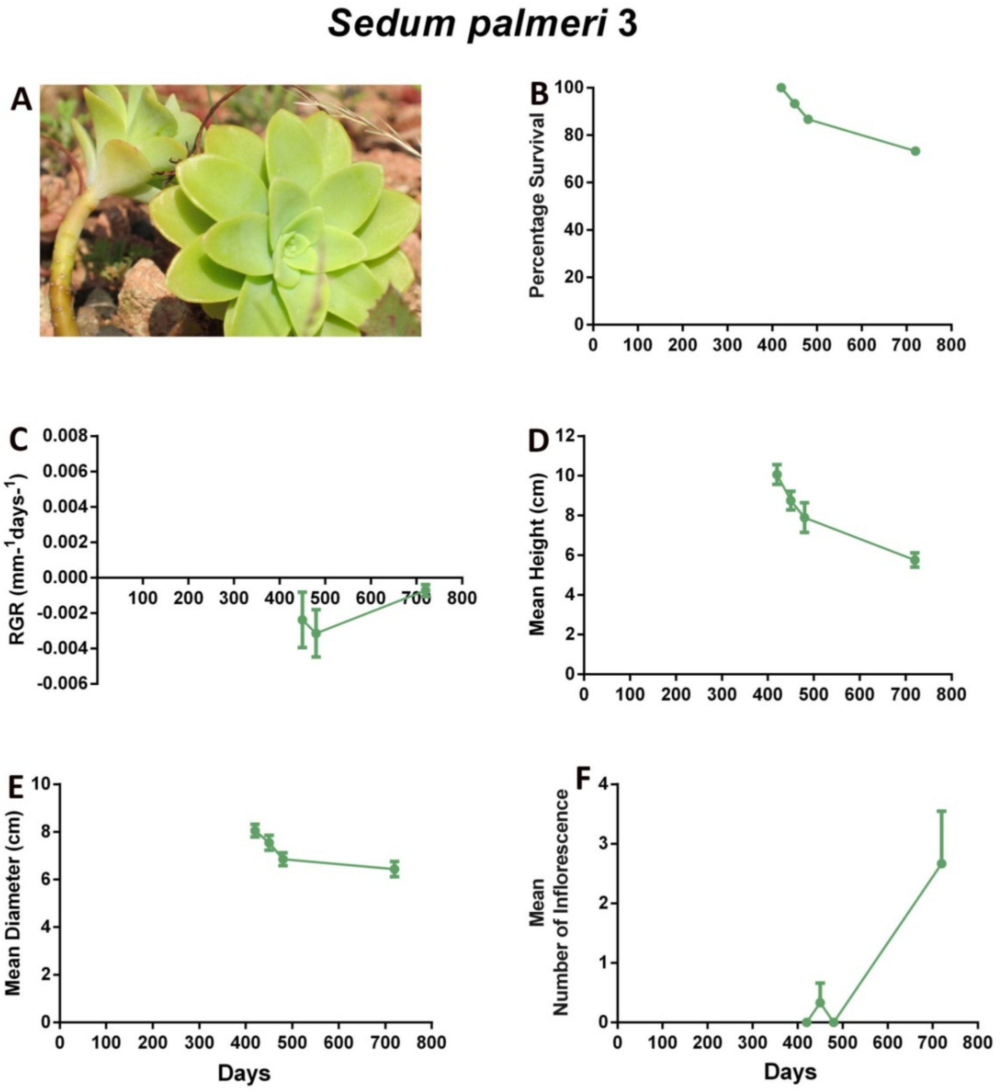


Figure 5.2.22 A) *Sedum palmeri* 3, Repeated measures of: B) Percentage survival, C) Diameter Relative Growth Rate, D) Mean Height, E) Mean Diameter, F) Mean Number of Flowers. ±SEM bars only for between depths subjects. Negative RGR is due to reduction in size due to dehydration from cold damage.

Sedum palmeri ssp. *rubromarginatum*

S. palmeri ssp. *rubromarginatum* had 66 % survival by the end of the experiment (Figure 5.2.23 B). The first loss of plants at the beginning of the experiment was also due to birds picking the plants. The diameter RGR measurements were also negative during the entire screening (Figure 5.2.23 C). Diameter had a constant growth until after the winter, when diameter decreased (Figure 5.2.23 D). The height measurements showed a constant decrease, but this is probably not caused by a loss of leaves or biomass, but it is the result of the arching habit of the species (Figure 5.2.23 D).

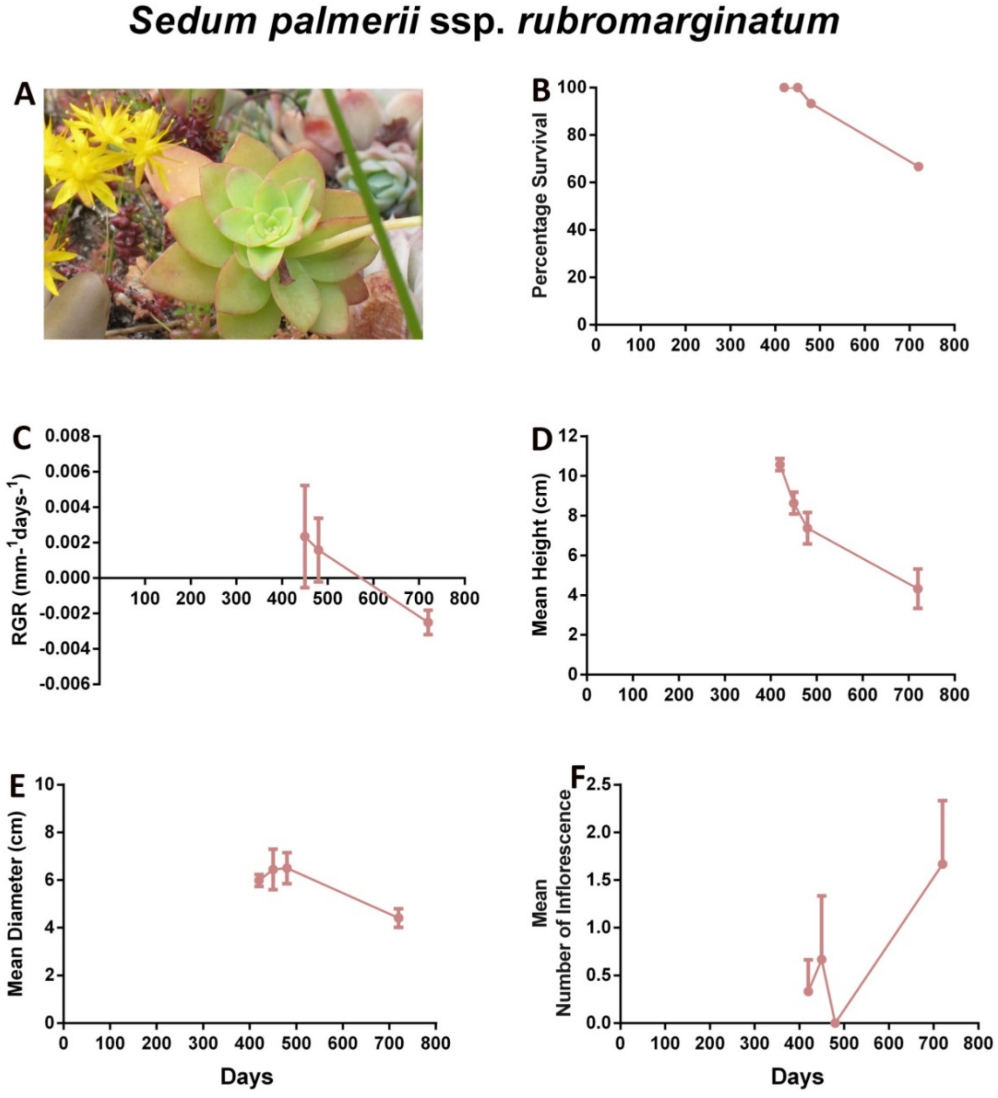


Figure 5.2.23 A) *S. palmeri* spp. *rubromarginatum,* Repeated measures of: B) Percentage survival, C) Diameter Relative Growth Rate, D) Mean Height, E) Mean Diameter, F) Mean Number of Flowers. ±SEM bars only for between depths subjects. Negative RGR is due to reduction in size due to dehydration from cold damage.

Sedum palmeri 1

Sedum palmeri 1 lost over half its population after the winter, with 53 % survival by the end of the experiment (Figure 5.2.24 B). The diameter RGR showed a decrease in growth after establishment, with a later recovery at the end of the autumn, and again a decrease of growth by the end of winter (Figure 5.2.24 C). The height of the plant constantly decreased until the end of the screening; again, this species has an arching habit, which can account for this seemingly negative growth (Figure 5.2.24 D).

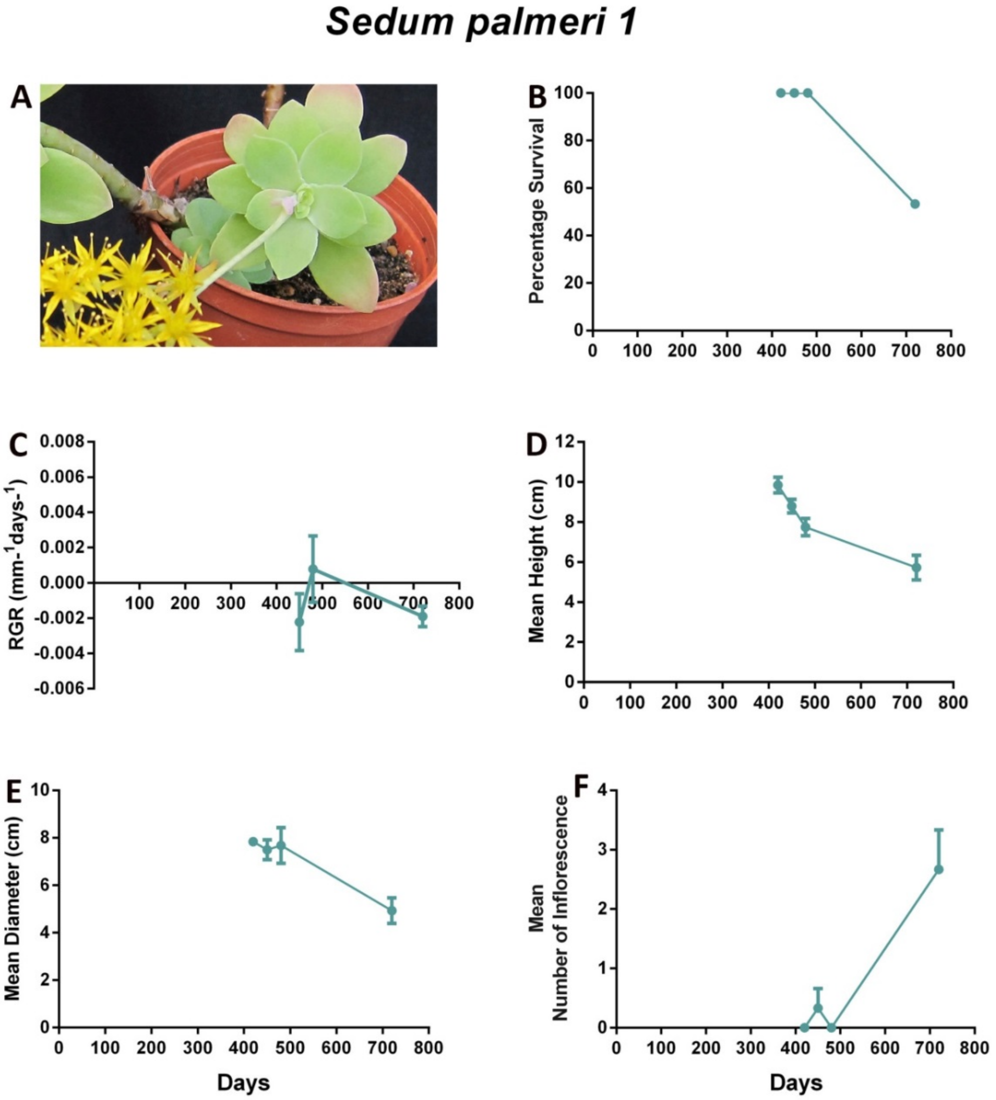


Figure 5.2.24 A) *Sedum palmeri* 1, Repeated measures of: B) Percentage survival, C) Diameter Relative Growth Rate, D) Mean Height, E) Mean Diameter, F) Mean Number of Flowers. ±SEM bars only for between depths subjects. Negative RGR is due to reduction in size due to dehydration from cold damage.

Sedum hultenii

S. hultenii had a very poor performance and all plants died after the winter (Figure 5.2.25 B). The diameter RGR decrease after planting, and there was some diameter growth before the onset of winter (Figure 5.2.25 C). No flowers were ever recorded (Figure 5.2.25 F).

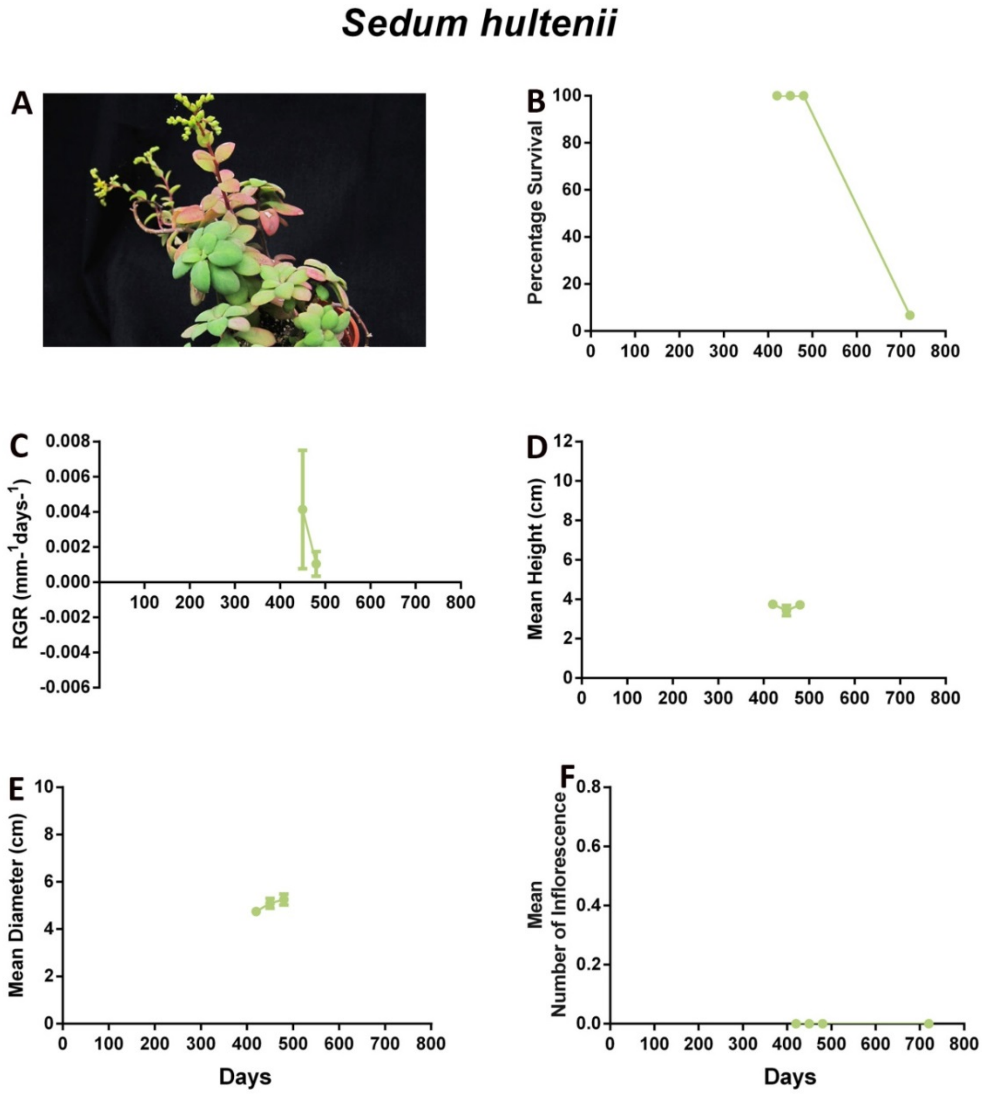


Figure 5.2.25 A) *Sedum palmeri* 1, Repeated measures of: B) Percentage survival, C) Diameter Relative Growth Rate, D) Mean Height, E) Mean Diameter, F) Mean Number of Flowers. ±SEM bars only for between depths subjects. Negative RGR is due to reduction in size due to dehydration from cold damage.

Pachyphytum compactum

The small *P. compactum* had 80% survival by the end of the screening (Figure 5.2.26 B). The diameter RGR attained a high initial growth period, but after the measurement of the first growing season the diameter RGR decreased over the remaining course of the screening (Figure 5.2.26 C). Nevertheless, the diameter increased over the growing season, and only after the winter decreased (Figure 5.2.26 E).

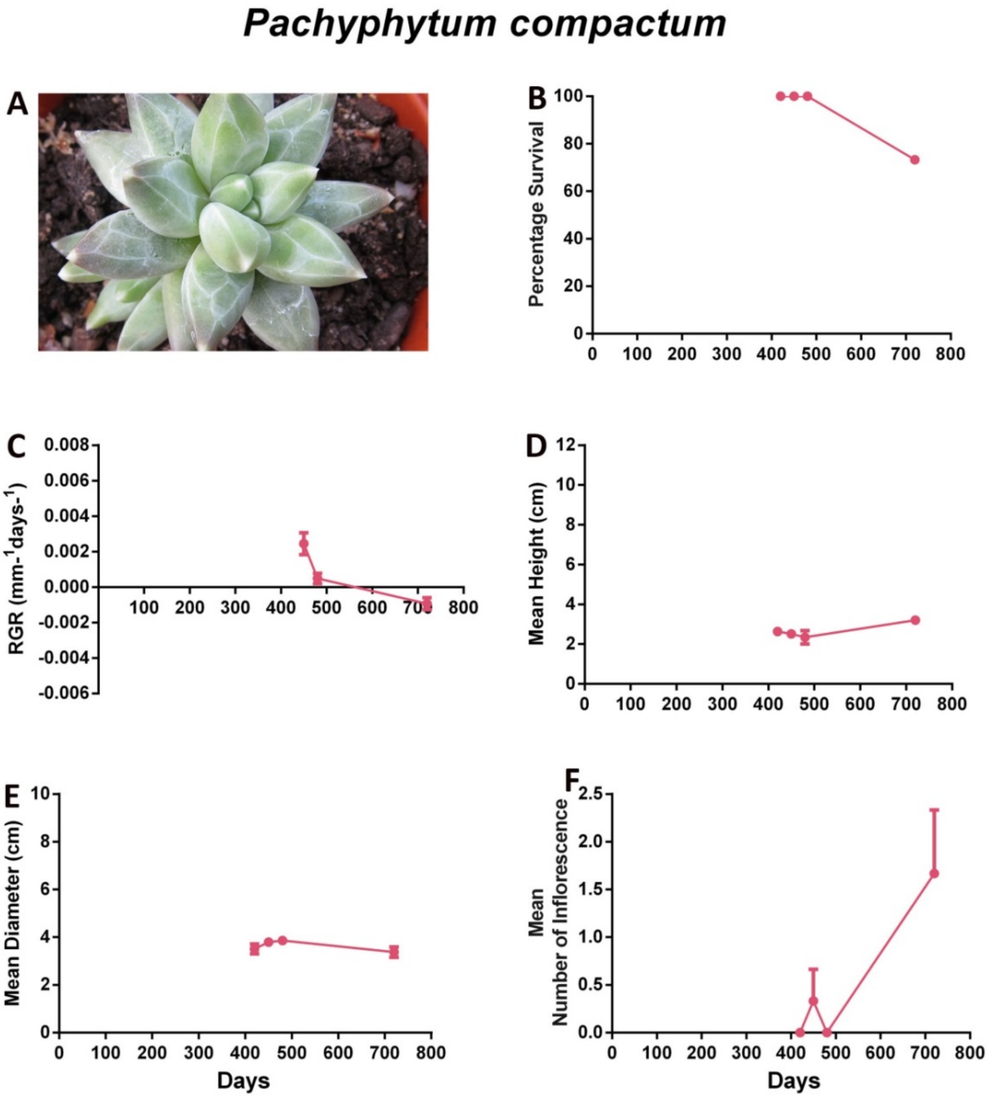


Figure 5.2.26 A) *P. compactum* %, Repeated measures of: B) Percentage survival, C) Diameter Relative Growth Rate, D) Mean Height, E) Mean Diameter, F) Mean Number of Flowers. ±SEM bars only for between depths subjects. Negative RGR is due to reduction in size due to dehydration from cold damage.

5.2.5.5 Percentage survival, diameter RGR, diameter and height models

There were clear significant differences in survival for the 5 different taxa described above ($p<0.001$, Greenhouse-Geisser correction) (Figure 5.2.27). The repeated measures for the diameter relative growth rate (RGR) was significant for the whole model with ($p=0.014$, Greenhouse-Geisser), but there were no significant differences between species ($p>0.05$) (Figure 5.2.28). The mean diameter and height measurements were significant for the whole model ($p<0.001$ Greenhouse-Geisser). The final dry biomass accumulation was significantly different between the 5 plants ($p<0.05$) (Figure 5.2.29). Although the total biomass was significantly different between species, the fact that the differences between diameters RGR were no different, suggests that the changes in biomass have to do more with the relative size of the species than with the growth they achieved during the screening.

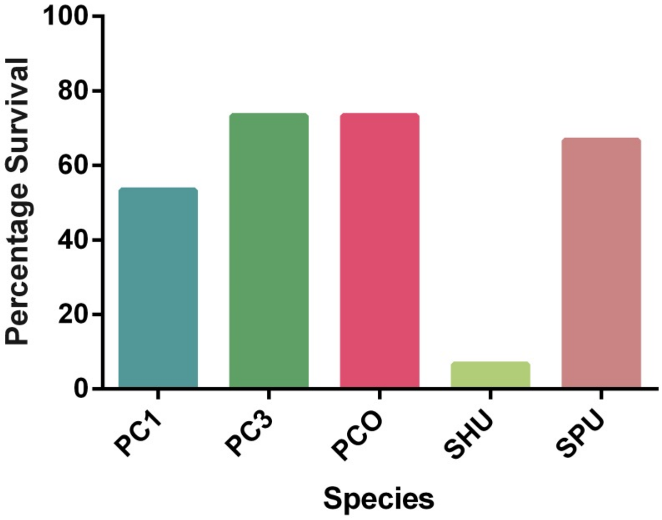


Figure 5.2.27 Survival ±SEM for *S. palmeri* 1 (PC1), *S. palmeri* 3 (PC3), *Pachyphytum compactum* (PCO), *S. hultenii* (SHU), *S. palmeri* spp. *rubromarginatum* (SPU).

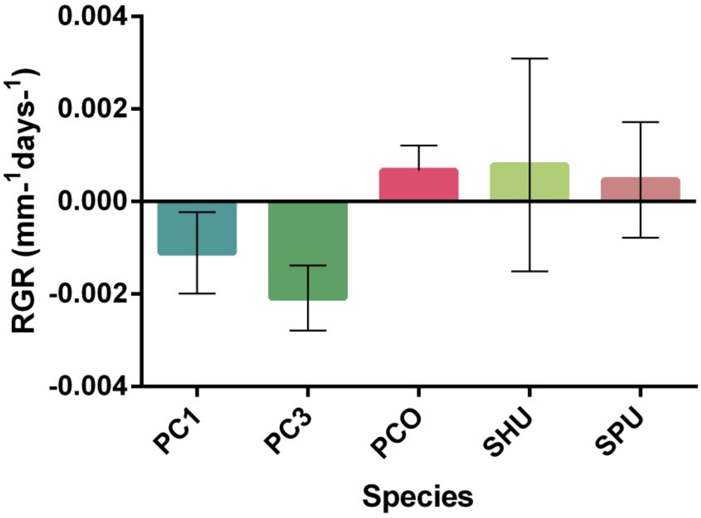


Figure 5.2.28 Diameter RGR ±SEM for *S. palmeri* 1 (PC1), *S. palmeri* 3 (PC3), *Pachyphytum compactum* (PCO), *S. hultenii* (SHU), *S. palmeri* spp. *rubromarginatum* (SPU). Negative RGR is due to reduction in size due to dehydration from cold damage.

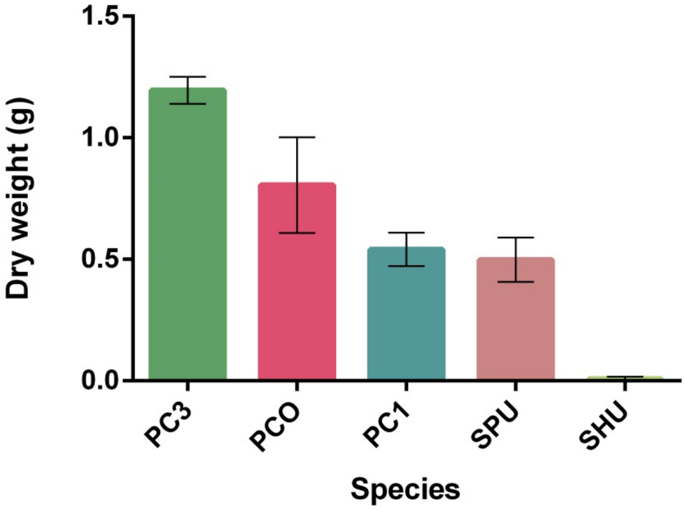


Figure 5.2.29 Total biomass ±SEM for *S. palmeri* 3 (PC3), *Pachyphytum compactum* (PCO), *S. palmeri* 1 (PC1), *S. hultenii* (SHU).

5.2.5.6 Flowers

Percentage of flowering plants

There were significant differences in the number of flowering plants between species during the entire screening ($p<0.001$, Greenhouse-Geisser correction). *Echeveria secunda*, *Sedum moranense* 138, *S. moranense* 4, and *S. moranense* 7 achieved 100 % of flowering individuals; significantly higher ($p<0.05$) than *E. prolifica*, *E. strictiflora*, *P. glutinicaule*, *S. commixtum*, *S. griseum*, *S. hernandezii*, *S. lucidum*, *S. mexicanum* and *S. stahlii* (Figure 5.2.30).

S. moranense Nursery and *S. reptans* developed flowers on more than 90 % of its plants; significantly higher ($p<0.05$) than *E. prolifica*, *P. glutinicaule*, *S. commixtum*, *S. hernandezii*, *S. lucidum*, *S. mexicanum* and *S. stahlii* (Figure 5.2.30). Species X *Graptoveria* 'Acaulis', *S. confusum* 'Large Form', *S. confusum* 'Cerro de la Yerba', *S.* 'Rockery Challenger', *S.* x *luteoviride* developed flowers on 88 % of their plants (Figure 5.2.30). X *Graptoveria* 'Acaulis'and *S.* x *luteoviride* had significantly higher flowering ($p<0.05$) than *E. prolifica*, *P. glutinicaule*, *S. commixtum*, *S. hernandezii*, *S. lucidum*, *S. mexicanum*. Species *S. confusum* 'Large Form' and *S. confusum* 'Cerro de la Yerba' also had significantly more flowers ($p<0.05$) than the above same species as well as *S. stahlii*. *S.* 'Rockery Challenger' flowered significantly more than *E. prolifica*, *S. commixtum*, *S. hernandezii*, *S. lucidum*, *S. mexicanum* and *S. stahlii* ($p<0.05$).

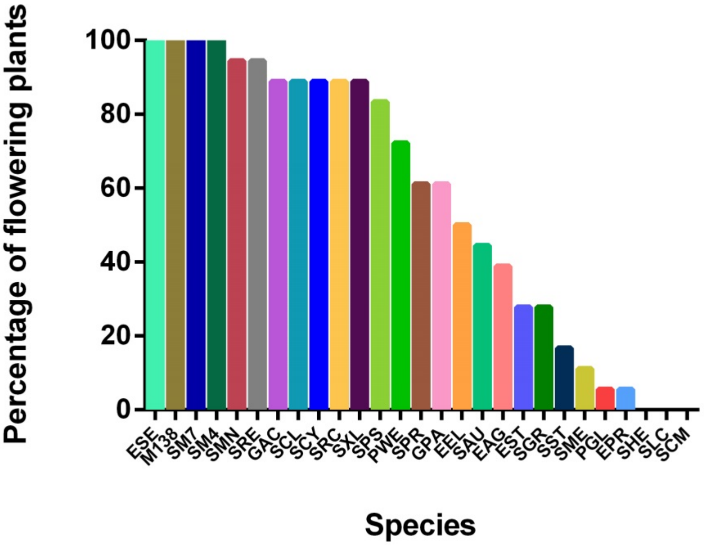


Figure 5.2.30 Percentage of flowering plants per species for *Echeveria secunda* (ESE), *Sedum moranense* 138 (M138), *S. moranense* 7 (SM7), *S. moranense* 4 (SM4), *S. moranense* Nursery (SMN), *S. reptans* (SRE), X *Graptoveria* 'Acaulis' (GAC), *S. confusum* Large Form (SCL), *S. confusum* Cerro de la Yerba (SCY), *S.* "Rockery Challenger" (SRC), *S.* x *luteoviride* (SXL), *S.* "Spiral Stairs" (SPS), *Pachyphytum werdermannii* (PWE), *S. dendroideum* ssp. *praealtum* (SPR), *Graptopetalum paraguayense* ssp. *Bernalense* (GPS), *E. elegans* (EEG), *S. australe* (SAU), *E. agavoides* (EAG), *E. strictiflora* (EST), *S. griseum* (SGR), *S. stahlii* (SST), *S. mexicanum, P. glutinicaule* (PGL), *E. prolifica* (EPR), *S. hernandezii* (SHE), *S. lucidum* (SLC), *S. commixtum* (SCM).

For the second set of plants of the screening, the differences between the repeated measurements of the percentage of flowering plants per species were highly significant (p<0.001, Greenhouse-Geisser correction). Surprisingly, there were no significant differences in flowering between individual species (p>0.05 Tukey HSD, for all combinations of plants) (Figure 5.2.31) in flowering despite the broad range of flowering behaviour observed.

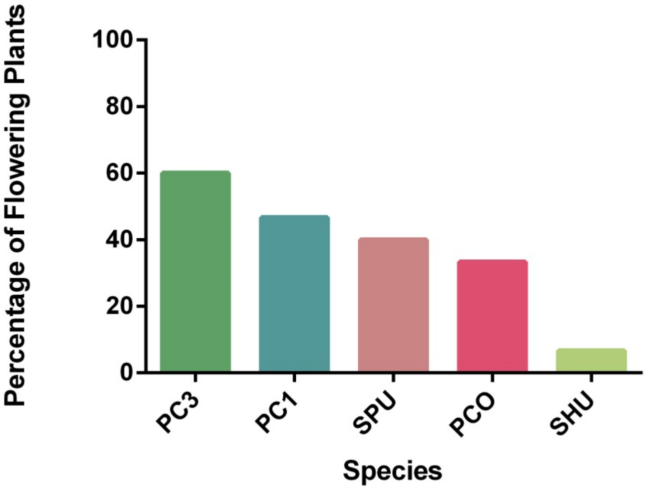
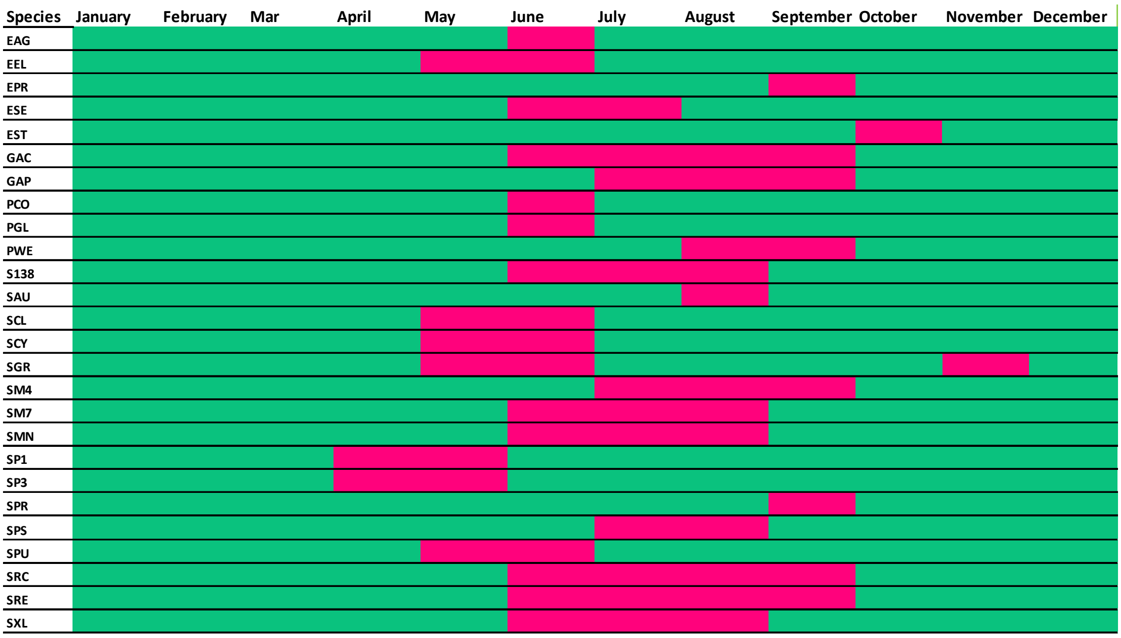


Figure 5.2.31 Percentage of flowering plants per species for *Sedum palmeri* 3 (PC3), *Sedum palmeri* 1 (PC1), *Sedum palmeri* spp. *rubromarginatum* (SPU), *Pachyphytum compactum* (PCO), *Sedum hultenii* (SHU).

The flowering phenology

The flowering phenology of the Mexican Crassulaceae species in the UK showed a response change in the Cfb climate that was in starkly contrast to the observed in their normal habitats in Mexico. In the UK the flowering periods were the following.

Species with the longest flowering period included: *S. reptans, S.* ‘Rockery Challenger’ and X *Graptoveria* ‘Acaulis’ (Table 5.2.3). In these cases, most of the individuals of each species flowered during the summer months. The changes in flower opening time of some species were minimal, while other species had larger difference.



Species	January	February	Mar	April	May	June	July	August	September	October	November	December
EAG	🟩	🟩	🟩	🟩	🟩	🟥	🟩	🟩	🟩	🟩	🟩	🟩
EEL	🟩	🟩	🟩	🟩	🟥	🟥	🟩	🟩	🟩	🟩	🟩	🟩
EPR	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟥	🟩	🟩	🟩
ESE	🟩	🟩	🟩	🟩	🟩	🟥	🟥	🟩	🟩	🟩	🟩	🟩
EST	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟥	🟩	🟩
GAC	🟩	🟩	🟩	🟩	🟩	🟥	🟥	🟥	🟥	🟩	🟩	🟩
GAP	🟩	🟩	🟩	🟩	🟩	🟩	🟥	🟥	🟥	🟩	🟩	🟩
PCO	🟩	🟩	🟩	🟩	🟩	🟥	🟩	🟩	🟩	🟩	🟩	🟩
PGL	🟩	🟩	🟩	🟩	🟩	🟥	🟩	🟩	🟩	🟩	🟩	🟩
PWE	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟥	🟥	🟩	🟩	🟩
S138	🟩	🟩	🟩	🟩	🟩	🟥	🟥	🟥	🟩	🟩	🟩	🟩
SAU	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟥	🟩	🟩	🟩	🟩
SCL	🟩	🟩	🟩	🟩	🟥	🟥	🟩	🟩	🟩	🟩	🟩	🟩
SCY	🟩	🟩	🟩	🟩	🟥	🟥	🟩	🟩	🟩	🟩	🟩	🟩
SGR	🟩	🟩	🟩	🟩	🟥	🟥	🟩	🟩	🟩	🟩	🟥	🟩
SM4	🟩	🟩	🟩	🟩	🟩	🟩	🟥	🟥	🟥	🟩	🟩	🟩
SM7	🟩	🟩	🟩	🟩	🟩	🟥	🟥	🟥	🟩	🟩	🟩	🟩
SMN	🟩	🟩	🟩	🟩	🟩	🟥	🟥	🟥	🟩	🟩	🟩	🟩
SP1	🟩	🟩	🟩	🟥	🟥	🟩	🟩	🟩	🟩	🟩	🟩	🟩
SP3	🟩	🟩	🟩	🟥	🟥	🟩	🟩	🟩	🟩	🟩	🟩	🟩
SPR	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟥	🟩	🟩	🟩
SPS	🟩	🟩	🟩	🟩	🟩	🟩	🟥	🟥	🟩	🟩	🟩	🟩
SPU	🟩	🟩	🟩	🟩	🟥	🟥	🟩	🟩	🟩	🟩	🟩	🟩
SRC	🟩	🟩	🟩	🟩	🟩	🟥	🟥	🟥	🟥	🟩	🟩	🟩
SRE	🟩	🟩	🟩	🟩	🟩	🟥	🟥	🟥	🟥	🟩	🟩	🟩
SXL	🟩	🟩	🟩	🟩	🟩	🟥	🟥	🟥	🟩	🟩	🟩	🟩

Table 5.2.3 Flowering distribution between the months of January to December. Species that did not flower due to low survival are not included. EAG *Echeveria agavoides,* EEL *E. elegans,* EPR *E. prolifica,* ESE *E. secunda* fa. *secunda,* EST *E. strictiflora,* GAC X *Graptoveria* ‘Acaulis’, GAP *Graptopetalum paraguayense* ssp. bernalense, PCO, *P. compactum,* PGL *Pachyphytum glutinicaule,* PWE *Pachyphytum werdermannii,* S138 *S. moranense* 138, SAU *S. australe,* SCL *S. confusum* Large Form, SYC *S. confusum* Cerro de la Yerba, SGR *S. griseum,* SM4 *S. moranense* 4, SM7 *S. moranense* 7, SMN *S. moranense* Nursery, SP1 *Sedum palmeri* 1, SP3 *S. palmeri* 3, SPR *S. dendroideum* ssp. *praealtum,* SPS *S.* “Spiral Stairs”, SPU *S. palmeri* ssp. *rubromarginatum* SRC *S.* “Rockery Challenger”, SRE *S. reptans,* SXL *S.* x *luteoviride.*

The varieties of *S. palmeri,* which in their native habitat flower from March to April (Acevedo-Rosas et al., 2004), flowered in the Cfb from April to May (Table 5.2.3); a difference of only month between the climates. In contrast, species like *S. reptans,* which also flower in its native habitat from March to April (Etter and Kristen, 1997), did not flowered in the UK until June and remained flowering up to September (Table 5.2.3). These changes in flower phenology surely respond to several environmental factors, but the most evident ones are the temperature and day length, since most of the species flowered during the warmest and longest days of the year May to September (Table 5.2.3). This might be related to the different photo-periods and daily and nocturnal temperatures (Chew et al., 2012) of the Cfb climate from their native habitat.

Considering the common used *Crassulaceae* species in Cfb climates (for example *S. acre, S. album, S. floriferum, S. Autumn Joy', S. hipanicum, S. kamthaticum, S. reflexum, S. sexangulare, S. spathifolium, S. spurium, Sempervivum arachnoideum* and *S. tectorum*), the combined flowering period spreads from the middle of May to the middle of November. In this case, the selected Mexican species do not lengthen this period much, since only the *S. palmeri* varieties flowered in April, while *S. griseum* although was able to flower during November did not performance well on the roof (Table 5.2.3). Nevertheless, Aigner (2005) has observed that flowers of species of the genus *Dudleya* are visited by up to 24 different taxa of pollinators, (such as solitary bees, bumblebees and hummingbirds) and even though a study of this sort has not been performed on *Echeveria* species, the fact that the inflorescence architecture of the two genera (*Echeveria* and *Dudleya*) are so similar suggests similar pollinator interactions may occur. In this way while flowering period may no differ between Mexican and European species, ecosystem services may be enhance by the new species incorporation into the palette

5.2.6 Discussion

The screening of the 32 Mexican Crassulaceae plants in a Cfb climate (warm temperate, fully humid, with warm summer), classified as groundcover, subshrub and rosette species, permitted the investigation of the performance of potential new plants to integrate into the plant palette for extensive green roofs in Cfb climates, such as the UK. The location of the roof, in Sheffield, gave the opportunity to test the plants in a far cooler and wetter microclimate than a location in the south of the UK would have provided. As the results suggest the physiographic origin of the species does not guarantee an improved survival of the species in these more extreme conditions. Although the plant selection methodology targeted plants from areas with similar climates to Cfb, an exact match was not possible due to the latitude, altitude and topographic differences between Mexico and the UK. Nevertheless, some of the species were able to adapt to the conditions of the Cfb, and indeed grew quite vigorously. If their performance does not guarantee their incorporation as fast ground cover species into the Cfb plant palette, they do however; contribute to the texture, colour and aesthetics of the extensive green roofs. In this way the successful identification of several species in this study may provide candidates for the enhancement of existing *Sedum* roofs and the services they provide

Figure 5.2.32 *S. palmeri* flowering at the beginning of May 2014 on the Demonstration Roof of the Green Roof Centre of the University of Sheffield.

Figure 5.2.33 *Echeveria elegans* flowering the first week of June 2014 on the Demonstration Roof of the Green Roof Centre of the University of Sheffield.

Figure 5.2.34 ***Sedum palmeri, S. reptans*** **and** ***E. elegans*** **flowering at the first week of June 2014 on the Demonstration Roof of the Green Roof Centre of the University of Sheffield.**

For the ground cover species tested in the study, all the varieties of *Sedum moranense* displayed the best performance; their survival, diameter RGR, their diameter, and number of flowering plants were the highest of all the species. Nevertheless, this species does not present any particularly special aesthetic characteristics, which could improve the aesthetics of the already present *Sedum* roof palette. The flowering period of all the tested plants of this species was across, June, July and August, with July as the month with the highest number of plants in flower (Table 5.2.3). This coincides with the flowering of species already used in the UK, like *Sedum album* that also possesses white flowers and is a much more vigorous plant. In spite this, further experiments with the incorporation of *Sedum moranense* varieties in typical communities of *Sedum* extensive roofs could provide information about the added benefits that these species may deliver.

The two other species with the best groundcover performance were *Sedum reptans* and *Sedum* 'Rockery Challenger' but these species, are not much more vigorous than the regularly used species in the UK *Sedum* extensive roofs and, again their aesthetic characteristics are no better. The remaining ground cover species did not perform well. For this reason it is probably not advisable to use them on the roofs of Cfb climates, such as the UK.

The subshrub species are plants that, even though inadequate ground cover species can provide different heights and structure to the extensive roofs, which might improve characteristics such as roof insulation by the creation of air pockets (Kolb and Schwarz 1986 cited by (Cook-Patton and Bauerle, 2012)), and different plant structure for invertebrates (Brenneisen, 2003). Of the subshrub species, the plants with the best performance were the *Sedum confusum* varieties (Large Form, and Cerro de la Yerba), *Sedum dendroideum* spp. *praealtum* and *Sedum* x *luteoviride.* These species showed the strongest diameter RGR of the subshrub group, although this was very low compared to the ground cover species *S. moranense.* Nevertheless, their height, between 4 and 10 cm, their large leaves and their contrastingly structure make them good candidate species to provide structural diversity on extensive *Sedum* roofs. Further research on their contribution to microhabitats for invertebrates, roof insulation by creating air pockets, and public reception of their aesthetics may provide further information on the future use of these species for green roof improvement.

Other subshrub species from this study that can be recommended for incorporation into the plant palette for Cfb green roofs are *Sedum palmeri* 1, *S. palmeri* 3 and *Sedum palmeri* subsp. *rubromarginatum.* These three varieties of *Sedum palmeri* did not have a very high RGR, but this could be due to the plant adaptability response in growth form to the dehydration from wind, as explained in the results section. Nevertheless, they had a high survival rate and their form, colour and structure can contribute to the aesthetic and biodiversity aspects of the roofs. Even though the use of rooted cuttings were used for plant establishment in the screening, due to their slow growth, if any of the subshrub species are going to be used in Cfb climate green roofs, it would be advisable to use plugs with branched plants to achieve a faster establishment and greater coverage.

The rosette forming species cannot provide fast ground cover either, but with this group of plants, their use on green roofs can add, as with the subshrub species, different structure diversity that can help to attract wild-life and improve the overall aesthetics of the roof. The rosette species providing the best performance were *Echeveria secunda* fa. *secunda, Echeveria elegans, Pachyphytum werdermannii, Pachyphytum compactum,* X *Graptoveria* ‘Acaulis’, and *Graptopetalum paraguayense* ssp. *bernalense.* These species are slow growing, but their inclusion in green roofs can dramatically enhance the aesthetics of a roof as can be seen in their incorporation in the Demonstration Roof of the Green Roof Centre in Sheffield (Figure 5.2.32 to Figure 5.2.34). The flowers of *Echeveria secunda* fa. *secunda* and *Echeveria elegans* provide enough nectar to constantly attract bumblebees and bees to the top of an 8 story building roof. Future research about the nectar production of *Echeveria* species in both Cwb and Cfb green roofs and the identification and habits of the foraging bees, could be incorporated into current research on bee habitat-creation on the roofs.

5.3 Competition between selected Mexican Crassulaceae species and European species

After the first year of the screening of the twenty-seven Mexican crassulacean ecotypes some selected species were tested in a competition experiment with European *Sedum* species already in use on green roofs in the UK. The screening provided initial data concerning the performance of the selected species with a Mexican plant community assemblage but not in the context of the European species most commonly used on green roofs. For this reason a competition experiment comparing the effects of different planting densities was necessary to determine if the selected Mexican Crassulaceae species can be incorporated into the common Cfb *Sedum* green roof. Expansion of the green roof palette will require the inclusion of compatible plant types, and if these Mexican species become dominated by the extant range of *Sedum* cover plants used, the their usefulness is very limited.

The definition of competition between plants depends much on the area of study. From the perspective of a population biologist, for example, competition between plants, intra or interspecific, is studied mainly for the outcome of their interaction, (i.e. their net reproductive rate R0) (Silverstown and Lovett-Doust, 1993). As Gibson et al. (1999) points out, this definition is too narrow, since competition can also be measured through other vegetative characteristics of plants. In a broader definition, competition can be defined as “the effect one species has on another”. For Grime (1979) competition is “*…the tendency of neighbouring plants to utilise the same quantum of light, ion of mineral nutrient, molecule of water, or volume of space*”. Competition in these terms will change according to the inherent “tendency of the plants” to use the available resources and will change as a consequence of external factors as well. Some of the external factors that limit the production of plant material in ecosystems included abiotic stress, where the deficiency of water, light or nutrients and/or non optimal temperatures reduce the growth or photosynthetic production of the plant (Grime, 1977, Grime, 2001). Biotic stressors that influence competition include the incidence of fungal or bacterial pathogens or herbivory by insects. External factors related to the physical destruction of plant material by animals, man, wind, frost, fire, etc. are known as disturbance (Grime, 1977, Grime, 2001).

The combination of stress and disturbance factors generates three possible habitats where plants can live. According to Grime (1977), these types of habitats hold plants with three type of strategies respectively: **low disturbance-low stress** habitats are associated with competitive plants, **high disturbance-low stress** with ruderal plants, **low disturbance and high stress** with stress-tolerant plants. The last combination, high disturbance-high stress, does not possess any strategy, since no plant can survive in this type of habitat (Grime, 1977). Since, in nature, we can find a gradient between the three extreme habitats, Grime notes that plants, in response, can have secondary strategies in the established phase, where we can find competitive ruderals, stress-tolerant ruderals, stress-tolerant competitors and competitor-stress-tolerant-ruderal strategists.

Succulent plants, and in the particular case of this research, Mexican Crassulaceae species, are stress-tolerant plants. The characteristics of these plants (see Chapter 2.2) allow them to live in areas where competitors or ruderals would not survive, due to the constant stressful and unproductive conditions of the habitat (Grime, 2001). Shallow extensive green roofs are dominated by *Sedum* species because they are stress-tolerant plants that can live in the stressful environment of the roof. The successful incorporation of the selected Mexican Crassulaceae species in to the extensive green roofs of Cfb climates, like in the UK, will depend on the abilities of two groups of stress tolerant plants to co-habit in this environment. European species are more tolerant to cold and wet winters; while Mexican species are more tolerant to high temperatures and drought. With the exception of previously described screening, it was possible to observe which species exhibited different structures, shapes and colours of leaves and flowers in contrast to the general European *Sedum* plant palette. With the subsequent competition experiment, the interaction of the two groups was explored, with particular emphasis on their competitive abilities and the possibility of coexistence in a roof top setting.

5.3.1 Preliminary considerations in the experimental design

Many different designs of competition experiments have been developed in fields such as plant ecology and agriculture. Each discipline aims to answer specific competition questions or resolve specific problems. The selection of a methodology, however, depends not only on the field of study, but on other factors such as the species to be tested, the designated purpose of the crop (for agriculture, ecology, landscape, etc.) and the availability of resources like water, light, nutrients and space. Competition experiments in the field of landscape are difficult to find. For this reason, therefore, approaches from different disciplines need to be adapted to the field.

Another important consideration in the experimental design is the difference between intraspecific and interspecific competition. Intraspecific competition is applied to the competition between plants of the same kind (i.e. in monocultures in which the densities are changed). In this scenario, the main observations are on the effects of planting density on crop performance (Park et al., 2003). In interspecific competition, the competition is between two different species or kinds of plants. In this case, the effects of both species on each other at different planting densities are studied (Firbank and Watkinson, 1987, Park et al., 2003). In both designs, other factors such as the availability of nutrients (like high and low nitrogen substrates), or different watering regimes, can be added to the experiments, depending on the resources that are of main interest (Freckleton and Watkinson, 2000, Gibson et al., 1999).

Another consideration when designing a competition experiment is the difference between the outcome of competition and the effects of species on each other. While the first term refers to the end point composition of a community, the second one refers only to the effect that one species has on the other (Gibson et al., 1999).

5.3.2 Brief description of available designs

The replacement series or substitutive design

Replacement series or substitutive design first used by de Wit (1960), and incorporates two species grown in both monocultures and mixed crops. The mixed crops are set up in various sets with different proportions of both species. In both the monocultures and mixed crops a constant density is kept (Figure 5.3.1) (Snaydon, 1991). The use of the same overall density leads to a lower density of the components of the mixed crop compared to the density of the monoculture, and therefore it is not possible to distinguish between intraspecific and interspecific effects (Freckleton and Watkinson, 2000, Snaydon, 1991, Gibson et al., 1999, Park et al., 2003).

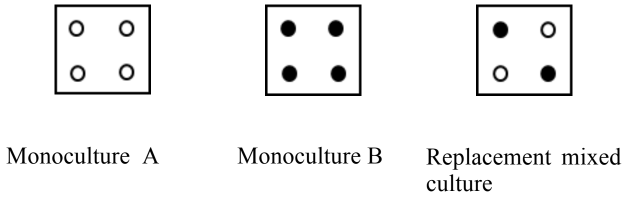


Figure 5.3.1 Replacement design, adapted from (Snaydon, 1991).

Simple pair-wise design

Simple pair-wise design (Figure 5.3.2) develops plots in which the ratio of two species in the mixtures is usually 1:1. This kind of experiment can be used in combination with different factors (Gibson et al., 1999, Mahmoud and Grime, 1976).

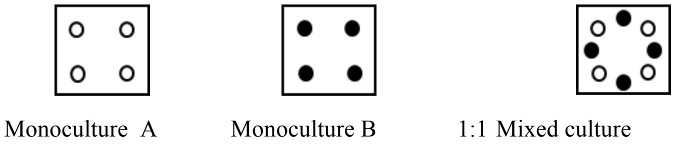
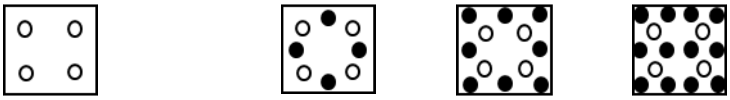


Figure 5.3.2 Simple pair-wise design, adapted from (Gibson et al., 1999, Grime, 1979)

Additive designs

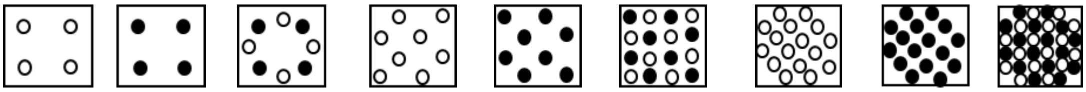
In additive design the density of both the mixed crops and of the monocultures changes, as well as the proportions of the species in the mixed crops (Freckleton and Watkinson, 2000, Gibson et al., 1999, Park et al., 2003, Snaydon, 1991). In the partial additive design (Figure 5.3.3), used mainly in agriculture, the crop density remains constant in all sets, while the weed density increases (Park et al., 2003). In this case, the main interest is to know the effect of weeds on the crop's yield; therefore no information on the effect of the crop on the weeds can be deduced. Usually the weed monocultures are not included in the partially additive experiments.



Monoculture Partial additive design mixed culture

Figure 5.3.3 Partial additive design adapted from (Park et al., 2003)

A more complete additive design is known as the additive series (Figure 5.3.4). In this case the proportions and densities of both species increase; therefore, intraspecific and interspecific effects can be compared at different densities in both species. In additive series design, analysis by response surface method is suggested (Gibson et al., 1999).

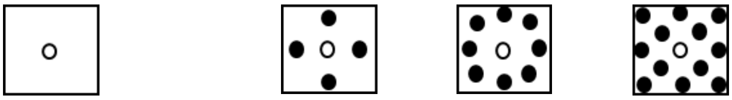


Monocultures density (4) Mixed culture Monocultures density (8) Mixed culture Monoculture density (16) Mixed culture

Figure 5.3.4 Additive series, adapted from (Snaydon, 1991).

Target neighbour design

Target neighbour design has special interest in the performance of an individual in relationship with its neighbours or associates (Figure 5.3.5). It is different from the above experiments because of its focus on the target individual rather than in the performance of a population. The arrangement of the plots is constructed using one individual of a particular species, surrounded in each set by different densities of plants of the same or other species (Gibson et al., 1999, Mack and Harper, 1977, Park et al., 2003). The main problem with this design is that the increasing in density of the neighbours has an effect, not only on the target plant, but on the performance of the neighbours themselves. Therefore, the only information one can obtain from the target-neighbour designs is that of the performance of the individual target plant, but no competition information is extractable for both species (Gibson et al., 1999).



Target plant Target plant with (4), (8) and (12) neighbours.

Figure 5.3.5 Target-neighbour design adapted from (Gibson et al., 1999).

5.3.3 Aims and objectives of the competition experiment

In the following competition experiments the selected Mexican green roof species were tested in the UK, to answer questions about their interaction with a European Sedum species. Can the Mexican species vie for space or will they be outcompeted by the fast growing European species?

Since the main aim of this research is to incorporate Mexican Crassulaceae species into the UK plants palette for green roofs, knowledge about their performance in combination with other commonly used species is needed. Exploring the performance of the selected Mexican species with all the species used in the UK for green roofs would require multiple experimental designs with a large quantity of resources and space. For these reasons representative European *Sedum* species were selected. The key characteristic for the selection of the European species was vigour and a high growth rate to fully test the Mexican plants. As Gibson et al. (1999) point out there is limited predictive power in short term competition experiments, especially when considering the long term interaction of the plants. Nevertheless from the perspective of green roof research, where the aim is to achieve the maximum ground cover as soon as possible to prevent the establishment of weeds, a short term study may shed light on the interaction of different species. Here, plant competition during green roof establishment is the focus.

5.3.3.1 Methods and Materials

During the month of August 2012 five simple pair-wise design competition experiments were setup on the roof of the building of the Education Department of the University of Sheffield, to observe the growth of Mexican Crassulaceae species in an interspecific competition conditions. The selected Mexican species, were *Sedum confusum* 'Large Form'*, Sedum* x *luteoviride, Echeveria secunda, E. elegans*, and *E. strictiflora.* The *Sedum* species were selected because they had a high survival rate and a markedly different growth form from the European species, and can therefor bring different textures to the roof. The *Echeveria species* were also selected on the basis of their survival potential and aesthetics qualities. Nevertheless *E. strictiflora* suffered total mortality after the second winter, and as will be described, most the plants of the competition experiment died as well for this species.

For the experiments investigation the Mexican *Sedum* species, a mix of three European species was treated single unit in the design: *Sedum album, S. acre* and *S. reflexum.* For the experiments of the *Echeveria* species, a mix of two European species was used as a single competition unit *Sempervivum tectorum* and *Sempervivum arachnoideum.* The incorporation of more than one species in the competition unit was developed to grow the Mexican species in a plot resembling closely the characteristics of a common *Sedum* roof.

The five experiments were set up on the roof of the 8 storey building of the School of Education of the University of Sheffield. The trays' dimensions were 38 x 24 x 8 cm depth. Each tray contained DVB-12 Zinco drainage layer and a filter sheet (SF) and was filled up with a substrate composed of 55% crushed brick, 30% pumice, 10% coir and 5% composted bark, a mix used in in the Green Roof Centre of the University of Sheffield as a standard mix that does not uses peat The size of the trays was selected to reduce the surface area and space to enable the effects the competition to be clearly observed.

The plant material was obtained from several sources. *Echeveria* and *Sempervivum* rosettes used on the experiments, and plants of *Sedum acre* and *S. reflexum* were bought from Kernock Park Plants. *S. album, S.* x *luteoviride* and *S. confusum* "Large Form" were propagated in the installations of the Sheffield Botanical Garden. All chosen rosette plants had a minimum diameter of 35 mm and a maximum diameter of 45 mm. The sedum species were prepared by cutting them into 7 cm shoots and them were left to heal. Cuttings were then planted in plug trays of 20 x 20 x 55 mm with a mix of 80% J. Arthur Bower's Cactus Compost and 20 % grit at 3 cm deep to develop plants of homogenous size. Plants were left to root for four weeks and there were then were transferred for two more weeks to acclimatize out in the exterior.

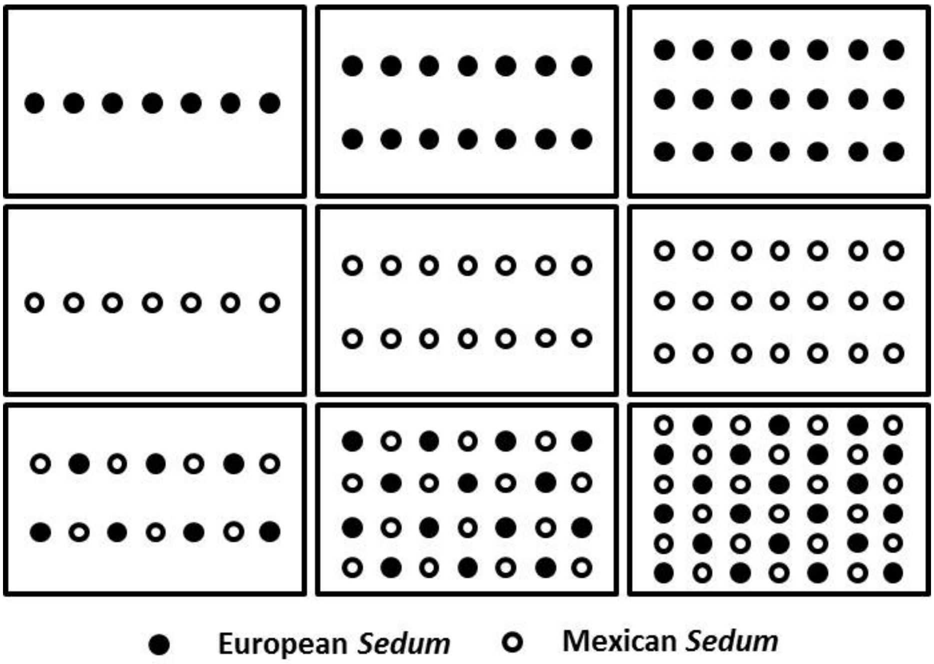


Figure 5.3.6 Set up of experimental unit for European and Mexican *Sedum* species at 7, 14 and 21 plants density and monocultures and mix-cultures.

On the second week of August 2012 the competition experiments were set up on the roof. For the *Sedum* species, each experimental unit was formed by three trays of monocultures and three trays of mix-cultures at three densities (7, 14 and 21 plants) with plants in a grid arrangement. The densities in multiples of seven were selected to take into account the maximum number of plants that the tray could contain in the mix-culture, giving room for plant growth take place.

The mix-culture trays had an alternated arrangment of an European *Sedum* cutting and one Mexican *Sedum* cutting (Figure 5.3.6). Each unit was replicated three times. This arrangement was set up for each one of the Mexican *Sedums*: *S. confusum* and *S.* x *luteoviride.*

For the rosette species, each experimental unit was formed by three trays of monocultures and three trays of mix-cultures at three densities 5, 10 and 15 with plants disposed in a grid arrangement. The density in this case was in multiples 5 due to the greater size of the rosette plants. The arrangement of plants followed the same pattern as with the *Sedum* (Figure 5.3.7).

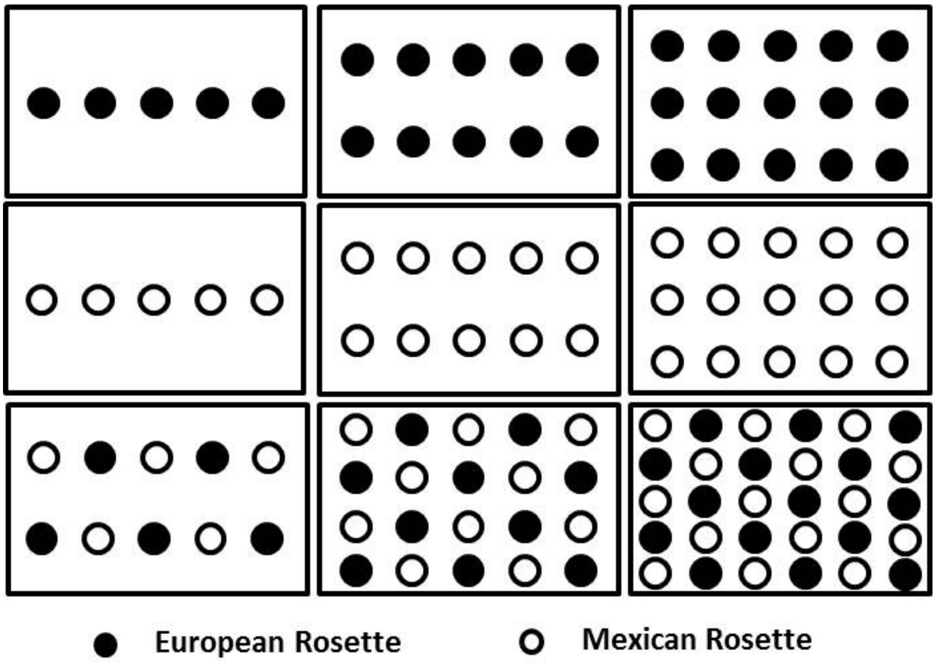


Figure 5.3.7 Set up of experimental unit for European and Mexican *Sedum* species at 7, 14 and 21 plants density and monocultures and mix-cultures.

The specific disposition of the plants in the grid arrangement was designed to provide all plants at each density with the same space and, in the mix cultures, to have a balance of European and Mexican species. All experimental units were orientated towards the north, with no shade from the trays nor adjacent buildings. All trays were watered during the first five weeks, twice a week, until water started to leak from the bottom of the trays.

5.3.3.2 Data collection

For the dry weights, 5 plants of the same initial size of each species were oven-dried. All plants of the experiment were harvested on day 240. Shoots and roots were divided, and roots were washed to remove substrate. All plant material was dried at 70° C over three days or longer, depending on weight stability. Dry masses were then weighed. Air temperature data was obtained from Sheffield Weather Data (Sheffield-Weather-Page, 2011b).

5.3.3.3 Data analysis

The data set of each Mexican species in competition with the European mix was analysed using a two way ANOVA with factors type of culture (monoculture and competition) and species (European mix and Mexican species) for each density. A further multiple comparisons of means, using Tukey HSD, was applied. The data were analysed with program R Studio version 3.0.1 (R Development Core Team, 2013).

5.3.3.4 Results

Sedum confusum

There were no significant differences for either of the species (*S.* confusum and the European mix culture) between monoculture and mix-culture at **7 plants density** ($p>0.05$, Tukey HSD). European Mix had a significantly higher RGR than *S. confusum* “Large Form” in both mix and monoculture ($p<0.01$, Tukey HSD) (Figure 5.3.8). **For density 14**, there were no significant differences between the mix and monoculture, neither for *S. confusum,* nor for the European Mix ($p>0.05$, Tukey HSD). In both cases, the European Mix had significantly higher RGR than *S. confusum* ($p<0.01$, Tukey HSD) (Figure 5.3.8). **For density 21**, the European Mix did not present any significant differences between mix and monoculture ($p>0.05$, Tukey HSD), while for *Sedum confusum* “Large Form” the RGR of the monoculture was significantly higher than the mix-culture ($p<0.01$, Tukey HSD) (Figure 5.3.8). In mono and mix-culture, the RGR of the European Mix was significantly higher than *S. confusum* ($p<0.001$, Tukey HSD) (Figure 5.3.8).

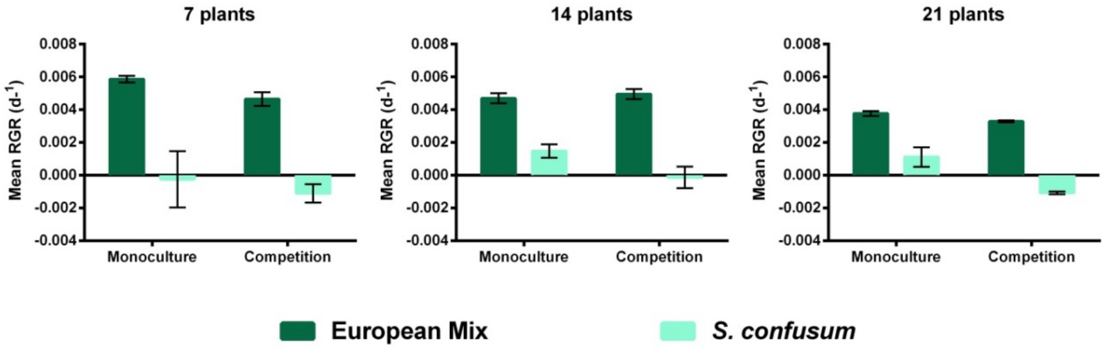


Figure 5.3.8 Mean Relative Growth Rate of *Sedum confusum* in monocultures and in competition with the European Mix at 7, 14, and 21 plant densities with ± SEM.

The fact that *Sedum confusum* had a much lower RGR than the European Mix in Cfb climate is interesting considering that in the Cwb (Mexico) climate *S. confusum* was one of the most vigorous species of the experiment (Section 3.3.2.3). The lower growth of this species on the Cfb (Sheffield) climate might be caused by the lower temperatures and lower solar radiations that some plants experienced. Woodward and Pigott (1975) found that *Sedum telephium* had a reduction in growth at higher altitudes when in competition with *S. roseae* and attributed this to the lower temperatures and possible lower solar irradiances at higher zones. This suggests that some of the factors responsible for the reduction in RGR and the cost of stress-tolerance mechanisms of *S. confusum,* to the extent of minimizing growth, could include the cooler and darker winters experienced in the Cfb climate. In consequence, if *S. confusum* is under higher stress in an unfavourable Cfb climate, its competitive response to the European species is much lower than in the Cwb climate.

An alternative mechanism that could explain the poor behaviour of *Sedum confusum* in the competition plots is the relative size of the leaves of the species. All the European mix species (*S. album, S. acre* and *S. reflexum*) had small leaves, while *S. confusum* has much bigger leaves by comparison. Yates et al. (2010) found that, in areas with poor nutrient soils and dry hot summers, species with smaller leaves present a higher transpiration rate during winter and spring when more water is available. This allows the plants to have a higher and faster acquisition of nutrients from the rhizosphere when water is available, and the advantage of the available below-ground reserve in poor nutrient soils (Yates et al., 2010). Consequently, the bigger leaves of *S. confusum* were perhaps not able to take up as much nutrients as the small-leaved plants of the European Mix. It is important to note that, even though *S. confusum* presented such low growth, the survival of the species did not suffer. A longer term experiment could show whether the more aggressive growth of the European Mix outcompetes this species or if the slow, but constant, growth of *S. confusum* permits the development of sturdy low subshrubs.

Sedum x *luteoviride*

At **7 plants density** there were no significant differences for the European Mix between monoculture and the competition plots ($p>0.05$, Tukey HSD). Nevertheless, there was an increase in RGR in the competition plot. In contrast to *S.* x *luteoviride,* the monocultures RGRs were significantly higher than the competition plots ($p< 0.05$, Tukey HSD). Interestingly in the monoculture, *S.* x *luteoviride* had a significantly higher RGR than the European Mix ($p<0.05$), but in contrast, at the competition plot level the European Mix had a significantly higher RGR than *S.* x *luteoviride* ($p<0.01$, Tukey HSD) (Figure 5.3.9).

At **14 plants density,** neither Mexican nor the European mix showed any significant differences between monocultures and mix-cultures ($p>0.05$, Tukey HSD). There were no differences in RGR between species at any culture type either ($p>0.05$, Tukey HSD). At this density an apparent coexistence of both species was observed. This might be caused by the low amount of resources available to both species at this higher planting density, where both species arguably had to tolerate the stressful environment (Figure 5.3.9).

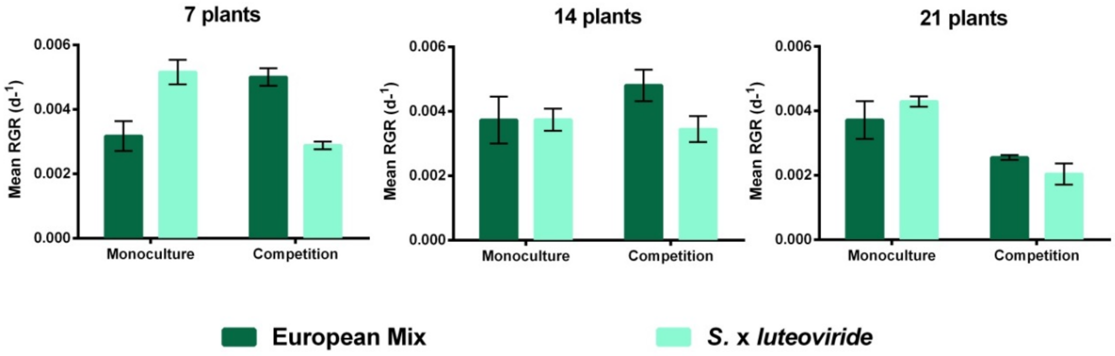


Figure 5.3.9 Mean Relative Growth Rate of *Sedum* x *luteoviride* in monocultures and in competition with European Mix at 7, 14, and 21 densities with ± SEM.

At **21 plants density,** the European Mix did not show any differences between mix-cultures and monocultures (p>0.05), while the *S.* x *luteoviride* monocultures performed significantly better than the competition plot (p<0.05, Tukey HSD). There were no differences between species under any culture arrangement (p>0.05, Tukey HSD). *S.* x *luteoviride* had a very low competitive ability in comparison to the European Mix at low densities, while at the medium and higher densities both groups had a similar RGR. In this case, both the European Mix and *S.* x *luteoviride* have small leaves, which probably, in contrast to the case of *S. confusum,* enable both species to acquire enough nutrients by transpiration and pull as mass flow from the roots. The time scale of the competition experiment was insignificant to show if this apparent coexistence can endure over longer periods of time (Figure 5.3.9).

Echeveria elegans

At **5 plant density,** monoculture and mix-culture did not show any significant differences in performance (p>0.05, Tukey HSD). In monoculture, *Echeveria elegans* was significantly greater than the European mix (p< 0.05, Tukey HSD) while at the mix-culture there were no significant differences between species (p> 0.05, Tukey HSD) (Figure 5.3.10). At **10 plant density,** the monoculture and the competition plots did not show any significant differences within species (p< 0.05, Tukey HSD) (Figure 5.3.10). In both types of planting at the 10 plants density, *Echeveria elegans* was significantly higher than the European mix (p< 0.01, Tukey HSD). At **15 plant densities** neither European Mix nor *E. elegans* had any significant differences in RGR between monocultures and mix-cultures within species (Figure 5.3.10). For both type of cultures *E. elegans* had significantly higher RGR (p<0.05) than the European Mix (Figure 5.3.10).

The experiment with rosette plants showed that this very slow growing species *E. elegans* does not induce much interspecific competition unless plants are grown in a tight space at very high density, and these effects were borderline significant. Although across the three densities *E.*

elegans had a higher RGR, its growth was not aggressive enough to have a deleterious effect on the growth of the European Mix.

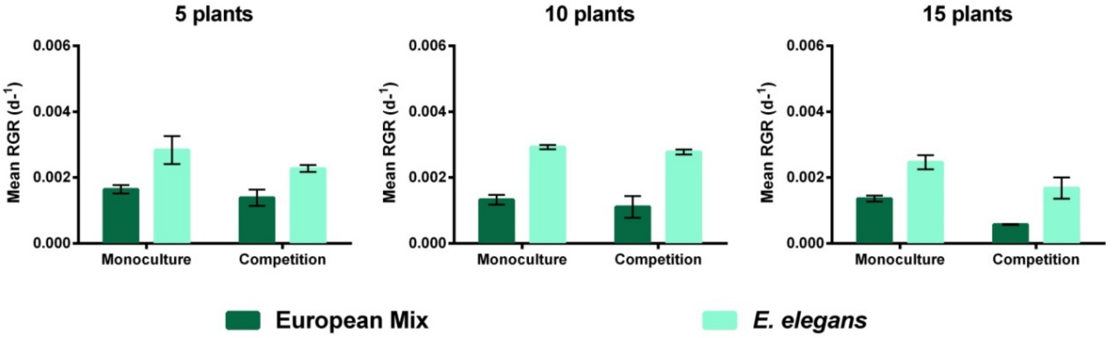


Figure 5.3.10 Mean Relative Growth Rate of *Echeveria elegans* in monocultures and in competition with European Mix at 7, 14, and 21 densities with ± SEM

Echeveria secunda

At 5 plants density there were no significant differences in RGR between mix-culture and mono culture; neither for *E. secunda* nor the European Mix ($p>0.05$, Tukey HSD) (Figure 5.3.11). There were no significant differences in RGR between species either ($p>0.05$, Tukey HSD). At 10 plants density no significant differences in RGR between culture types, either for *E. secunda* or for European Mix ($p>0.05$, Tukey HSD) (Figure 5.3.11). No significant differences in RGR between species were found ($p>0.05$ Tukey, HSD) (Figure 5.3.11). At 15 plants density there were no significant differences between type of cultures for either *E. secunda* or the European Mix ($p>0.05$, Tukey, HSD) (Figure 5.3.11), nevertheless, for the European Mix, the *p* value was borderline significant ($p=0.06$, Tukey, HSD), with higher RGR for the monocultures. The RGR was significantly higher for *Echeveria secunda* ($p< 0.01$, Tukey, HSD) (Figure 5.3.11) than for the European Mix. As with *Echeveria elegans,* the outcome between the European Mix and the *Echeveria secunda* does not show any obvious competition from any of the groups (Figure 5.3.11).

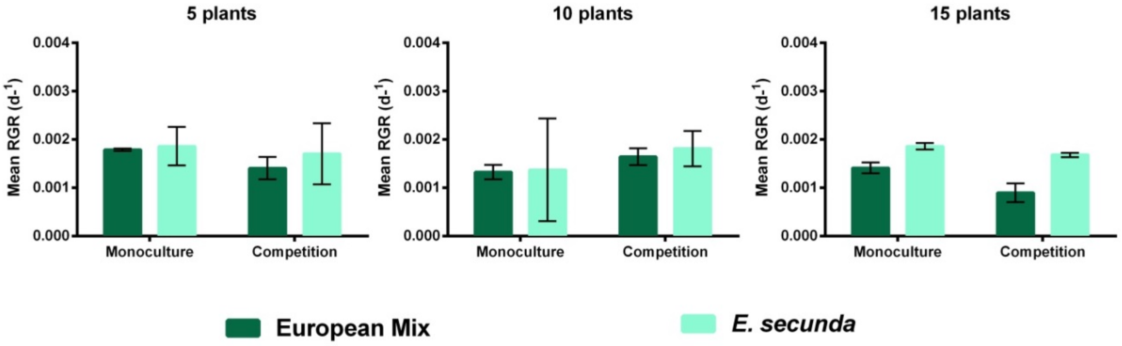


Figure 5.3.11 Mean Relative Growth Rate of *Echeveria secunda* in monocultures and in competition with European Mix at 7, 14, and 21 densities with ± SEM.

Echeveria strictiflora

This species had a high mortality over winter, and therefore it was impossible to have plants alive for each replication to perform the required statistics. *E. strictiflora* was, therefore completely uncompetitive.

It is important to notice that the RGR of the European rosette species selected for this experiment was very low, and a much different result and a more competitive system might have developed if rosette species with a higher RGR were selected such as *Sempervivum tectorum* or a more vigorous cultivar.

5.4 Conclusions

This chapter presented (a) the results of a screening and (b) a competition experiment with the aim of answering questions about the performance of Mexican Crassulaceae species, selected through the methodology developed in Chapter 2, for extensive green roofs of Cfb climates. The results of the screening concentrated on those species, which had the best survival performance in the Cfb climate, while the competition experiment shed some light on the interactions between the generally used European species in *Sedum* extensive green roofs with some of the successful species identified in the screening. This section summarises findings of the screening and the competition experiments to help answer the questions raised in the introduction to this chapter.

5.4.1 Can the Mexican Crassulaceae species targeted with the plant selection methodology of Chapter 2, survive on green roofs on Cfb climate?

During the screening, nineteen species, plus three species with a total of nine varieties, two garden hybrids, and two natural hybrids, were tested, with a combined total of thirty-two different taxa. From the initial list of the potential species selected for Cfb climates, only these taxa were screened due to the limited availability of plant material, appropriate size, or desired aesthetic characteristics. Some species on the list were not available from botanical collections and their native localities in Mexico are very remote. Other species were excluded because they are very slow growing and difficult to propagate, while other species are very small and also had a very slow growth.

Of the thirty-two tested taxa, twenty-three survived the Cfb climate. Of these twenty-three hardy species, seventeen had greater than 60 % survival. All forms of *Sedum moranense* and *S. confusum,* as well as *E. secunda* showed the most promise in terms of the higher survival. *Sedum moranense* and *E. secunda* are species that can be found at more than 3000 m.a.s.l. and therefore can experience very low temperatures in their natural habitats. The range of *S. confusum's* altitude is not described in the literature, but it can grow on *Pinus* and *Quercus* forests, and therefore it might be adapted to grow at high altitudes as well.

The cause of mortality for most of the species was almost invariable the extreme cold in combination with the high rainfall during the winters. In this regard, the Mexican territory has a very low percentage of areas that experience wet winters. The areas of Mexico with higher precipitation in winter, which are combined with lower temperatures, are usually found at very high altitudes where the plants experience very high solar radiation as well. For these reasons, the Cfb is a very difficult climatic combination to match within the Mexican territory. The fact that 50 per cent of the selected screened species survived the experiment was a good result, and lends support to the power of the selected methodology. Had there been the opportunity to extend the selection of species to wild collected and propagated material from specific provenances, this survival the range of species would likely been greater. Especially if species were collected at altitudes higher that 4000 m.a.s.l. from alpine communities.

5.4.2 Can the targeted Mexican Crassulaceae species have a good performance on green roofs on Cfb climate?

Those species with the best performance were also the species with the highest survival rates: the varieties of the ground cover species *S. moranense,* the two varieties of the subshrub *S. confusum¸* and the rosette forming *E. secunda,* as well as the subshrub *S. dendroideum* ssp. *praealtum* and *S* x *luteoviride.* The three different forms of *S. palmeri,* although they had a very low RGR, showed a constant growth and have a unique colour and texture that can bring some brightness to the European extensive green roof palette. *Echeveria elegans*, even though it did not have the best survival, had a very good performance in terms of aesthetics and probably nectar production, since was frequently visited by pollinators. The *Pachyphytum* species showed high survival, but because plants were established when small they did not have enough time to spread before the onset of winter. This slow growing species performed much better and had a better display when planting was as a big plant, as was seen in the Demonstration Roof of the Green Roof Centre of the University of Sheffield (Figure 5.2.34). Perhaps the use of the plugs would result in the successful incorporation of *Pachyphytum* species in to Cfb roofs.

It is important to note that most of these species had a very low relative growth rate, and therefore by no means can these taxa be used as substitutes for the already commonly used species on extensive green roofs of Cfb climates. Nevertheless, their incorporation into extensive green roofs can improve the texture, colour and type of flowers of the systems and this might improve the benefits for the wildlife on the green roofs and the overall aesthetics.

5.4.3 Can Mexican Crassulaceae species cohabit green roofs with generally used Crassulaceae species on Cfb climate?

The competition experiment showed that Mexican Crassulaceae species with broad and long leaves have a slower RGR if grown together with small leaf European *Sedum* species. This pattern was observed with *S. confusum* “Large Form”, but it would be expected to be a similar result with *S. confusum “*Cerro de la Yerba”, and with *S. dendroideum* ssp. *praealtum* as well as the three forms of *S. palmeri.* In spite of these differences in RGR, the survival of this species was 100 %. Considering that this species went through two winters with no mortality, even though the RGR was reduced, could enable this species to be used in extensive green roof assemblages. Its very slow growth rate, forming sturdy woody stems like the ones these broad leaf subshrubs achieved at the plots of the screening, could be beneficial to an extensive green roof over longer periods of time. For this, experiments of longer duration are required

The small leaf species, *S.* x *luteoviride,* showed that it can grow in a balanced interaction with small European *Sedum* species. The ground cover *S. moranense* showed a higher diameter RGR than *S.* x *luteoviride,* and this suggests that all the four varieties of the small leaf *S. moranense* might behave in the same way if grown with European *Sedum* species.

Both rosette species, *E. secunda* and *E. elegans,* in competition with the mix of *Sempervivum tectorum* and *S. arachnoideum* presented a balanced interaction. The experiments did not consider the potential competition between ground cover species such as *S. album,* and *Echeveria* species; nevertheless, if the two *Echeveria* species have a similar performance to that of the *Sempervivum* species, they might be successfully introduced on Cfb extensive green roofs for the same reasons. Other rosette species that had similar performance to the *Echeveria* species were *Pachyphytum compactum* and X *Graptoveria* “Acaulis”. Overall, the competition experiments demonstrated the potential of Mexican species to grow as part of a plant community assemblage alongside competitive and vigorous European species. For this reason the above species should be seriously considered for the established roof planting.

5.4.3.1 Which density-per-space unit of the Mexican species and the European species can bring a mutualistic interaction?

The planting density used for the tested Mexicans Crassulaceae species in future Cfb green roofs will depend on the type of plants requiered and the desired effect. The competition experiment showed that *S.* x *luteoviride* did not overtake the European Mix, and therefore this species can be planted at the same density as *S. album, S. acre* and *S. reflexum* which is usually around 10 to 20 plants per m^2 (Dunnett and Kingsbury, 2008, Snodgrass and Linda, 2010). The taller species, *S. dendroideum* ssp. *praealtum,* and *S. confusum* (both forms), do not work as ground cover species, and plugs of single shoot cuttings grow no more than 20 cm over two growing seasons. If this species will be used as a possible accent plant the density should be decided based upon the effect that it is intended to create, taking the growth into consideration. The rosette species like *Echeveria secunda* fa. *secunda, and E. elegans* and the *Pachyphytum* species as well, should be used in combination with ground cover species.

5.4.4 According to the survival and performance of the plant species tested on the screening, did the methodology accomplish its’ purpose of targeting species with potential to be used in Cfb climates?

The plant selection methodology was able to target enough species that demonstrated a good performance on the green roof of Cfb climate, but some improvements into more exact details of the provenance of the plants are needed. Even though the native altitude data of some of the species was found, the methodology did not include it as an independent factor since it was implied in terms of the native habitat's temperature range. Nevertheless, the plant selection showed that some of the species with the best performance in Cfb climates were native to the higher altitudes of Mexico. It is difficult to find specific native provenance data of plant species from both public and private plant collections, specifically of small plant communities but plant collection to find species inexact locations is highly recommended. In the case of this research the wide distribution of the plant species across the lower half of the North American Continent, at the increasingly security risk from drug gangs within the Mexican territory make this task impossible in terms of time, distance, safety and finances.

Despite the lack of altitude data of some for the species, it was possible to identify species that demonstrated have a good performance in Cfb roofs, and provided that they are not required as rapid ground cover species, they can be used as accent plants to improve aesthetics and/or biodiversity. Nevertheless, future research about the specific services these species can provide to the wildlife and to the roof and building itself is needed and it is necessary to stress out that the results of this research are just the observations of a short period. Longer observations about the changes on plants species composition and their relationship with fauna in the long term are necessary.

Chapter 6 Overall discussion and conclusions

The methodology for green roof plant selection, following the Köppen-Geiger-Kettek climatic classification and other key climatic parameters, presented in Chapter 2 was used, to target potential Crassulaceae candidate species for climates Cwb (**warm temperate, dry winter and warm summer**) and Cfb (**warm temperate, fully humid, and warm summer)**. The species are ecotypes selected for use in each climatic zone were tested on roofs of two cities in each of the climates: Twenty seven types for the Cwb climate of Mexico City, and thirty two types for the Cfb climate of Sheffield, UK. This section will answer the questions raised in the Introduction Chapter. Below the validity and power of the developed methodology, for the successful identification of green roof candidates is discussed.

6.1 Q1. Is it possible to develop a plant selection methodology to target Mexican Crassulaceae species for different climates? Which parameters should be considered in the plant selection methodology?

It was possible to develop a plant selection methodology to identify Mexican Crassulaceae species that could be suitable for green roofs of different climates. The use of the Köppen-Geiger climatic classification provided a broad tool of climatic definition as a methodological framework, to which more refined parameters were then incorporated. These extra parameters included the temperature variation due to altitude and the characterization of a wide range of microclimates, are absent from the global scale of the Köppen-Geiger classification. Minimum and maximum temperatures of habitat zones, annual precipitation and precipitation distribution have to be utilized as components in the selection model to obtain a detailed fine resolution map of those areas homologous to the green roof site of interests, which may contain potential candidate species. In this way, the target physiographic zone is further elucidated to enhance efficient identification and useful plant material.

The favoured aspect in which the native plants grow, the directed provenance of the species, so to speak was not a factor which was integrated in to the plant methodology,but it proved to be a determinant factor. It was especially observed in the Cwb climate, since several species that naturally occur on the north or east face of mountains in Mexico did not survive the intense solar radiation experienced on the Cwb roof during the dry winter and spring. Some examples of species that reported negatively in this way, and most probably due to their preference for shadier aspects are *Graptopetalum superbum* and *Pachyphytum hookeri.* Both of whom died back severely on the winter dry season. Nevertheless, this phenomenon was not observed in the Cfb climate, with species from similar partially shaded areas, probably due to the more homogeneous precipitation distribution, the lower level of solar radiation and the lower temperatures. In future research this parameter should be incorporated when possible.

Furthermore, the collection of future wild plant material for the purpose of green roofs testing should pay particular attention to the aspect of species in their native setting. The methodology can then became a sharpening tool to select on only a single plant species of family, but an entire green-roof analogous ecological niche in any climatic and physiographic zone. From this analogous niche, it may be possible to screen numerous diverse plant types with excellent potential as ecosystem service providers.

The further development of the plant methodology also helped to target key vegetation types or local habitats in the Mexican territory that fell within the broader physiographic zone or climatic range. This additional layer of information was effective in the identification of narrow and localized specific habitats, such as natural grasslands, xerophytic scrubs and deciduous tropical forests for the Cwb climates green roofs such as in Mexico City, and alpine grasslands and *Pinus-Quercus* forests for the Cfb climate scenario such as in Sheffield UK. With the collection of genotypes from a gradient of altitudes from the habitats mentioned above it can be possible to find plant material of other different 'life forms' (such as grasses, forbs, small shrubs, geophytes) with expectation of a higher probability of adaptation to the roof environment.

The use of tools like GIS and digital climatic and habitat maps were not incorporated into this research, but their future application would clearly be highly beneficial to achieve a greater climatic detail of the possible sources of plant material and also linking the areas where the plants are intended to be used. These tools will also be able to improve the success rate of the adaptation of the plants to their destined areas. Shared GIS and aps systems will also help in the logging of candidate species provenance data and enable multiple users to update the selected methodology criteria to strength the model. It is necessary to stress that, although species with different life forms must be targeted for roofs of Cwb climates, in Mexico, the Crassulaceae family is an important native group. Its use should be encouraged in Mexico and efforts should be made to broaden its number of species growing on green roofs. This is primary because many rare species are losing their habitats due to increasingly urbanization and uncontrolled expansion of farming. Research on the possibility of utilizing green roofs as designed *ex situ* conservation sites for native xerophyte plant species is advisable, and it should be promoted by centralised government invectives as green roofs currently are.

6.2 Q2 Can the selected Mexican Crassulaceae species survive and grow in the climates they were targeted on: Cfb (warm temperate, fully humid, and warm summer) Cwb (warm temperate, dry winter and warm summer)?

The methodology developed for candidate plant selection proved to be very successful at targeting possible species for green roofs of climates Cwb and Cfb. For the Cwb climate, in the Mexico City case study, sixteen species of the twenty-seven species from the chosen four genera of Crassulaceae displayed a good or medium performance in terms of growth and survival. For this reason they could, with some certainty, be incorporated in to the plant palette for the Cwb climate. Other species, however, did not have a rapid enough growth in the experiment, but this was probably due to interspecific competition from other more vigorous plants. In the Cfb climate, of the thirty-two ecotypes that were selected twenty-three survived the two harsh winters and cool wet summers, although not all of them demonstrated a good performance on the roof.

The case study in Mexico City for the Cwb climate (warm temperate, **dry winter** and warm summer) had the objective of determining the minimum substrate required for optimal plant growth and the best planting season for optima establishment of the Crassulaceae species. This was achieved with by means of an experiment with ten Mexican *Sedum* species. The results demonstrated that the optimum substrate depth for these Crassulaceae species was a minimum of 100 mm depth. The optimal planting season proved to be at the beginning of, or some weeks before, the rainy season, when sufficient water is available to ensure a successful initial establishment. Nevertheless, it was seen that highly succulent or hairy species, such as *Sedum allantoides* and *Echeveria pulvinata,* had problems with the high amounts of water and developed fungal rot. In these cases, the use of big plants, with fully developed root systems, is advisable to enhance establishment success and rate of colonisation of the green roof.

Species such as *Echeveria gigantea, Echeveria pringley* var. *parva* and *Pachyphytum fittkaui* performed exceptionally well in the Cwb climate and have a high aesthetic value which would by highly rewarding for the green roof palette. *Echeveria gigantea,* from the tropical deciduous forests of Mexico, not only is highly aesthetically attractive, but it also provides abundant nectar for hummingbirds such as the native species *Cinanthus latirostris.* This hummingbird inhabits areas of the same type of vegetation and its winter range has expanded due to habitat and food provision in the urban environment (Fogden et al., 2014). The frequent visits of this hummingbirds species to the Cwb study site in Mexico City, was of high value. Future work to record bird behaviour on these green roofs and their interactions with these plant species will do much to highlight the additional benefits of an expanded green roof palette.

In the Cfb climate (warm temperate, **fully humid**, and warm summer), a broad screening was used to test which of the selected species had the best performance. Although several species had a good survival, their growth in the Cfb climate was generally not very vigorous. This lack of vigour at horizontal spread strongly suggests that the Mexican species tested here cannot be used as alternative ground cover species in the Cfb environment, like the native European species. The Mexican species that were tested had a limited growth, but can nevertheless, be incorporated into the Cfb climate green roof plant palette as accent plants that will be able to provide different colour ranges and textures to the common *Sedum* roofs. Their future use as accent plants is strongly encouraged especially as their often impressive inflorescences seem to have provided ample nectar and pollen to local bees.

Some species were highly successful both in the Cwb and the Cfb climates such as *Sedum confusum* and *Echeveria elegans*. Nevertheless, these species showed a generally greater vigour in the Cwb Mexico City case studies, than in the Cfb Sheffield tests. This less vigorous growth could be attributed to the lower mean temperatures and the high frequency of freezing stress, which the species experienced in the Cfb climate. It was observed that plants were able to recover much faster and generally grow better after extended periods of drought stress than after any freezing stress, most likely to the limited and lower cellular damage caused by water loss compared to crystals formation. Overall, the methodology developed for selecting potential plant species from the Mexican territory was successful to target species that can grow in a wide and relatively extreme climatic spectrum.

6.3 Q3 Can Mexican Crassulaceae species improve extensive green roofs dominated by ground cover *Sedum*?

In Mexico, extensive green roofs are usually planted with three main native species, *Sedum moranense, Sedum dendroideum* ssp. *praealtum* and *S. griseum.* Non-native species, namely *Carpobrotus edulis* and *Kalanchoe* are also regularly incorporated, as well as other native *Agave* species (such as *Agave americana*) and *Opuntia* species, which are used as accent plants (personal visit to various green roofs of Mexico City during 2009, 2010, 2012). This very limited plant palette can be observed repeatedly in various green roofs of Mexico with only a few exceptions such as the green roof of CICEANA (Centro de Información y Comunicación Ambiental de Norte América) where a broader use of Cactaceae and bushes of *Pittocaulon praecox,* a native species of the pedregal habitat of Mexico City. On the green roof of the American School, in Mexico City, a wider variety of Crassulaceae species and native annuals, such as *Cosmos bipinnatus,* are also now integrated (Reyes-Santiago, 2013)

The first step to change these monotonous *Sedum* green roofs in the Cwb climate is to introduce a broader native *Crassulaceae* plant palette. The species that were successful in this research can be readily incorporated into the Mexican green roof industry, since it has been shown that the species can grow in exactly the same conditions as the usual installed green roofs in Mexico City. Future research into other plant forms will bring a richer plant palette. The use of native species from the Pedregal de San Angel, the xerophilous scrub reserve inside Mexico City, can provide additional suitable plant material like bulbs and forbs.

In the case of the Cfb climates, the competition experiments' results proved that the tested Mexican Crassulaceae species can grow together with the European *Sedum* species used in Cfb extensive green roofs. The introduction of Mexican Crassulaceae species can provide starkly different forms and colours in to extant and future green roofs dominated by *Sedum* species. The general inability of this species to germinate from seeds on the roofs, as well as on the ground level, make them a less risky exotic plant choice to introduce. These species cannot generally grow on ground level due to the higher moisture content of the soils, and therefore these species will not be able to grow successfully outside of the roof environment for which they are intended. *Sedum confusum* has been observed, as an escape growing in warmer areas of the UK like Cornwall but it has not became a dominant and competitive threat to native species (Randall, 2007) nevertheless its use should be avoided in these areas.

In the Cfb climate, future research on the appropriate methods by which to incorporate the successful Mexican selected species in to already established *Sedum* green roof planting systems will be able to help to develop less homogenous roofs and/or improve the already installed ones. Investigations concerning nectar and pollen production could shed light on the potential of this species to supply food to pollinators such as *Bombus lapidarious* which forages *Echeveria* species in the testing roofs.

6.4 Future research

A significant future venture in the extension of this work would be to strength the plant selection methodology by means of software development and find-scale GIS technology. In addition an assessment must be carried out of the full range of services that the tested plant species can provide. This is necessary, especially in Mexico, where the research that has been done has not yet been published in the public domain; thereby restricting the growth not only of the industry, but of the green roof services themselves. More research on cooling effects, and runoff mitigation, with native species, is vital for a healthier industry and to broaden the functions and importance of the green roofs in this area of the world. Further work with the Institute of Ecology of the UNAM (National Autonomous University of Mexico) and the Department of Zoology of Institute of Biology of the UNAM, and other key Mexican universities, can help with the research of wildlife on the extensive green roofs, and the green roof features required to support the best possible existent local fauna, such as birds, reptiles and invertebrates.

Appendix 1

Species	Location	Altitude	Light	Vegetation Type	P. Zone	Observations	Case Study
Dudleya pauciflora	San Pedro Martir, Baja California Norte	no data	sun/half shade	*Quercus* forest	MSBC	not hardy	UK
Echeveria affinis	Km 195 w durango	2070 m	sun/half shade	*Pinus-Quercus* forest	NMSO	not hardy	UK, MX
Echeveria agavoides	Hacienda de San Francisco, Villa de Arraiga, SLP	no data	sun/half shade	N. Grassland	MP	not hardy	UK, MX
Echeveria amoena	West hills Perote, Veracruz	2400 m	sun/half shade	S. X. scrub (rossette)	TVB	not hardy	MX
Echeveria bifida	7km N of Bernal	2075 m	Half shade	Semiarid grassland (mezquital)	MP	not hardy	MX
Echeveria calderoniae	Santa Bárbara, Ocampo, Guanajuato	2220 m	Half shade	*Quercus* forest	MP	not hardy	MX
Echeveria cante	S. Chapultepec, Zacatecas	falta	sun /half shade	*Pinus-Quercus* forest /grassland	MP	not hardy	MX
Echeveria chapalensis	around Lago Chapala	1500-1600 m	Half shade	Succulent xerophilous scrub	TVB	not hardy	MX
Echeveria chihuahensis	Cusarare waterfall Chihuahua	2100 m	sun/half shade	*Pinus-Quercus* forest	MP	not hardy	UK, MX
Echeveria coccinea	Mexico City, Pedregal	2500 m	sun/half shade	H. X. scrub-pedregal	TVB	not hardy	MX
Echeveria colorata	Laguna Sayula to Tapalata	2070 m	sun/half shade a	*Pinus-Quercus* forest	TVB	not hardy	MX
Echeveria craigiana	Barranca del Rio Uripe	1500-2400 m	sun/half shade	*Pinus-Quercus* forest	SMOC	hardy?	UK
Echeveria cuspidata	Cuahuila	2100 m	sun/half shade	W. X. scrub-piedmont/oak forest	SMO, MP	not hardy	MX
Echeveria crenulata	Cuernavaca Morelos	1530 m	sun/half shade	Deciduous tropical forest	TVB	not hardy	MX
Echeveria dactilyfera	Durango	2310 m	sun/half shade	*Quercus* forest	SMOC	not hardy	UK, MX
Echeveria derembergii	Oaxaca, Cerro Verde	1800 m	sun/half shade	Deciduous tropical forest	NMSO	not hardy	UK, MX
Echeveria elegans	Hidalgo, Mountains above Pachuca	Aprox. 2500 m	sun/half shade	*Pinus-Quercus* forest	TVB	probably hardy	UK, MX
Echeveria fimbriata	Tepoztlan, Morelos, Mx.	no data	sun/half shade	Deciduous tropical forest	TVB	not hardy	UK, MX
Echeveria fulgens	Jalisco Real Alto	no data	sun/half shade	no data	SMOC	not hardy	UK, MX
Echeveria gibbiglora	Mexico City, Pedregal	2500 m	sun/half shade	H. X. scrub-pedregal	TVB	not hardy	MX
Echeveria gigantea	Cerro de la yerba	no data	sun/half shade	Deciduous tropical forest	NMSO	not hardy	MX
Echeveria halbingeri	Hidalgo, near La Paila	1500 – 2000 m	sun/half shade	*Pinus-Quercus* forest	TVB	not hardy	MX

Echeveria harmsii	Hidalgo, west Jacala	no data	sun/half shade	*Pinus-Quercus* forest	TVB	not hardy	Non
Echeveria heterosepala	Puebla near Tehuacan	2100 m	sun	S. X. scrub (rossette)	TVB	not hardy/High sun exposure	Mx
Echeveria humilis	San Luis Potosí	arpox 1500 m	sun	Semiarid grassland (mezquital)	MP	not hardy, not in cultivation	Non
Echeveria juarezensis	Ixtlán, Oaxaca	no data	Half shade	*Pinus-Quercus* forest	NMSO	not hardy/ no for sun exposure	Non
Echeveria juliana	Cañón Rio Piaxtla, Durango	360 m	sun/half shade	Deciduous tropical forest	SMOC	new species	Non
Echeveria laui	Neat Tecomavaca	500 m	sun/half shade	Deciduous tropical forest	NMSO	super dry	MX
Echeveria leuchotricha	San Luis Atolotitlan	no data	sun/half shade	Deciduous tropical forest	NMSO	not hardy	MX
Echeveria lilacina	East of Rayones, Nuevo León	900 m	sun/half shade	*Quercus* forest	SMO	not hardy/single rosette	Non
Echeveria longissima var. aztatlensis	Near San Miguel Aztatla	no data	sun/half shade	S. X. scrub (sacrocaule)	NMSO	not hardy/hard in cultivation	MX
Echeveria lozanoi	Etzatlán west Guadalajara	2600 m	no data	Deciduous tropical forest	TVB	not in cultivation	Non
Echeveria lutea	Sierra Alvarez San Luis Potosí	1900 m	sun/half shade	W.X. scrub-piedmont/ microfilous_chaparral	MP	not hardy/no for sun exposure	Non
Echeveria lyonsii	Near Ciudad Victoria, Tamaulipas	1300 m	sun/half shade	*Quercus* forest/piedmont scrub		not hardy/no for sun exposure	Non
Echeveria megacalyx	San Juan Mixtepec, Neveria, Oaxaca	3000 m	shade	*Pinus* forest	NMSO	not hardy/no for sun exposure	Non
Echeveria minima	Hidalgo, Rio Talquillo	1300 m	Half shade	N. Grassland	MP	too tiny, not hardy	Non
Echeveria montana/nuda	Sierra San Felipe, Oaxaca	2500-2900 m	sun/half shade	*Pinus-Quercus* forest	NMSO	not available	Non
Echeveria mucronata	Mexico City, Cima road to Cuernavaca	3000 m	sun/half shade	*Pinus* forest	TVB	not hardy/no for sun exposure	Non
Echeveria nayaritensis	Near Santa Maria del Oro, Nayarit	no data	sun/half shade	N. Grassland	TVB	not hardy	MX
Echeveria nebularum	Ixtlán,Sierra de Juarez, Oaxaca	no data	no data	Deciduous tropical forest/ *Quercus-Pinus* forest	NMSO	epyphyte	Non
Echeveria novogaliciana	Jalisco, Aguascalientes	no data	sun/half shade	Deciduous tropical forest /*Quercus-Pinus* forest	MP	not hardy	Non
Echeveria nodulosa	Near Teotitlán, Oaxaca	no data	sun/half shade	Deciduous tropical forest	NMSO	not hardy	MX
Echeveria paniculata	México, Chihuahua	2000 m	sun/half shade	N. Grassland	SMOC	not hardy/no for sun exposure	Non
Echeveria patriotica	Mazamitla, Jalisco	2290 m	sun/half shade	*Pinus-Quercus* forest	TVB	not hardy	MX
Echeveria peacockii	Tehuacán, Puebla	1675 m	Half shade	S. X. scrub (rossette)	TVB, NMSO	not hardy/no for sun exposure	Non
Echeveria pilosa	Sierra Mixteca, Puebla	no data	sun/half shade	Deciduous tropical forest	NMSO	not available	MX?
Echeveria platyphylla	Mexico City	2500 m	sun/half shade	H. X. scrub-pedregal	TVB	deciduous can die	Non
Echeveria pringley var. *parva*	Near Tayaltita, Durango	1305 m	sun/half shade	Deciduous tropical forest /*Pinus-Quercus* forest	MP	not hardy	MX

Echeveria prolifica	Hidalgo, Puebla	no data	sun/half shade	*Pinus-Quercus* forest	TVB	not hardy	UK,MX
Echeveria pulidonis	Near Necaxa, Puebla	no data	sun/half shade	*Pinus-Quercus* forest	SMO	not hardy	Non
Echeveria pulvinata	Tomellin Canyon, Oaxaca	900 m	sun/half shade	Deciduous tropical forest / *Pinus-Quercus* forest	NMSO	not hardy	MX
Echeveria purepecha	Parangaricutiro, Michoacán	1900 m	sun/half shade	*Pinus* forest	TVB	not hardy/no for sun exposure	Non
Echeveria purpusorum	San Atolotitlán, Puebla-Oaxaca	2285 m	sun/half shdae	Deciduous tropical forest	NMSO	very slow growing	Non
Echeveria rudolfii	Tamaulipas,	1800-2000 m	sun/half shdae	W. X. scrub -piedmont	SMO	not hardy/no for sun exposure	Non
Echeveria roseiflora	Mascota, Jalisco	2150 m	sun/half shade	*Quercus* forest	TVB	new species	Non
Echeveria rubromarginata	Tepeaca, Puebla	1800-2000 m	sun/half shade	*Pinus-Quercus* forest	TVB	not hardy	MX
Echeveria runyonii	Cerro Bufa del Diente, San Carlos, Tamaulipas	no data	sun/half shade	Deciduous tropical forest	SMO	not hardy	MX
Echeveria schaffneri	West Doctor Arroyo, Nuevo León	1890 m	sun/half shade	W. X. scrub - microfilous/ chaparral	SMO	not hardy	MX
Echeveria secunda	Popocatepetl	3980 m	sun/half shade	N. Grassland	TVB	probably hardy	UK
Echeveria setosa var. *setosa*	Cerro de la Yerba, Puebla	2100 m	Half shade	Deciduous tropical forest / *Pinus-Quercus* forest	NMSO	not hardy, no for sun exposure	Non
Echeveria shaviana	Dulces Nombres, Nuevo León	1800 m	sun/half shade	*Pinus-Quercus* forest	SMO	not hardy	MX
Echeveria simulans	Caja Pinta, Nuevo León	800 to 1600 m	sun/half shade	W. X. scrub -piedmont	SMO	probably hardy	MX,UK
Echeveria spectabilis	Near Macuiltanguis, Sierra Juarez Oaxaca	2500 m	sun/half shade	*Pinus-Quercus* forest / Deciduous tropical forest	NMSO	not hardy, little bit shaggy	MX
Echeveria strictiflora	Dulces Nombres, Nuevo León	no data	sun/half shade	*Pinus-Quercus* forest	SMO	probably hardy	UK
Echeveria subalpina	Pico Orizaba	no data	sun/half shade	subalpine grassland	TVB	slow growing and solitary	UK
Echeveria subcorymbosa	Near Santiago Juxtlahuaca, Oaxaca	1800 m	sun/half shade	*Pinus-Quercus* forest	NMSO	not hardy, no for sun exposure	Non
Echeveria subrigida	Near Alvarez, San Luis Potosí	no data	sun/half shade	*Pinus-Quercus* forest	MP	not hardy	MX
Echeveria tamaulipana	Near Ciudad Victoria, Tamaulipas	800-1200 m	sun/half shade	*Pinus-Quercus* forest	SMO	not hardy/sun exposure/high moist	MX?
Echeveria tobarensis	Tovar, Durango	aprox 2000 m	sun/half shade	*Pinus-Quercus* forest	SMOC	not hardy	MX
Echeveria tolimanensis	Tolimán, Hidalgo	1500 m	sun/half shade	N. Grassland (mezquital)	MP	not hardy	MX
Echeveria tolucensis	Cerro Teresano, Toluca	2700 m	sun/half shade	*Pinus-Quercus* forest	TVB	probably hardy	UK
Echeveria trianthina	Tolantongo, Hidalgo	2000	sun/half shade	*Pinus-Quercus* forest	SMO	not hardy	MX

Echeveria turgida	South Viesca, Coahuila	no data	sun/half shade	N. Grassland	MP	not hardy	MX
Echeveria uhlii	Near Tamazulapan, Oaxaca	no data	Half shade	S. X. scrub (sacrocaule)	NMSO	not hardy, no for sun exposure	Non
Echeveria unguiculata	South Monterrey, Tamaulipas	no data	sun/half shade	W. X. scrub-microfilous/chaparral	MP	very dry environment	MX
Echeveria valvata	West of Luvianos, S. of México	1450 m	sun/half shade	Deciduous tropical forest	TVB	not hardy	MX
Echeveria walpoleana	Las Canoas, San Luis Potosí	no data	sun/half shade	W. X. scrub-piedmont	MP	not hardy	MX
Echeveria waltheri	Near Villa Guerrero, Estado de México	1880	sun/half shade	W. X. scrub-piedmont	TVB	not hardy	MX
Echeveria xichuensis	Tolantongo, Hidalgo	no data	sun/half shade	*Pinus-Quercus* forest	TVB	not hardy, no for sun exposure	MX
Graptopetalum bartramii	Madera, Chihuahua	no data	half shade	*Pinus-Quercus* forest	SMOC	not hardy, no for sun exposure	Non
Graptopetalum filiferum	Cañón del Cobre, Chihuahua	1300 m	sun/half shade	*Pinus-Quercus* forest	SMOC	too tiny/nor hardy	Non
Graptopetalum fruticosum	East Ciudad Guzmán, Jalisco	no data	sun/half shade	Deciduous tropical forest	TVB	not hardy	MX
Graptopetalum pachyphyllum	Ahualulco, San Luis Potosí	no data	sun/half shade	W. X. scrub microfilous	MP	not hardy/slow growing	Non
Graptopetalum paraguayense	probably Tamaulipas	no data	sun/half shade	no data	SMO	hardy	MX,UK
G. paraguayense bernalense	Tamaulipas	700-800 m	sun/half shade	no data	SMO	hardy	UK,MX
Pachyphytum brachetii	Near Actopan, Hidalgo	no data	sun/half shade	Semiarid grassland (mezquital)	MP	no data	UK,MX
Pachyphytum bracteousum	Near Metzquititlan, Hidalgo	1300 m	sun/half shade	S. X. scrub (sacrocaule)	SMOC	probably hardy	UK,MX
Pachyphytum brevifolium	Guanuajuato	1600 m	sun/half shade	W. X. scrub -piedmont	MP	not hardy	MX
Pachyphytum caesium	Near Presa de los Serna, Zacatecas	2000 m	half shade	Deciduous tropical forest	MP	not hardy, no for sun exposure	Non
Pachyphytum coeruleum	Cadereyta, Querétaro	no data	sun/half shade	N. Grassland	MP	slow growing	Non
Pachyphytum compactum	Near Colón, Querétaro	2100 m	sun/half shade	N. Grassland (mezquital)	MP	Probably hardy	UK
Pachyphytum contrerasii	Near, Zapopan, Jalisco	1400 m	sun/half shade	*Pinus-Quercus* forest	TVB	not hardy/high amount of water	Non
Pachyphytum fittkaui	Near, Balneario de Lourdes, San Luis Potosí	1700 m	sun/half shade	Grassland	MP	no data	MX
Pachyphytum garcieae	El Zapote, Qeretaro	1600 m	sun/half shade	N. Grassland (mezquital)	MP	no data	MX
Pachyphytum glutinicaule	Near Ixmiquilpan, Hidalgo	1550 m	sun/half shade	N. Grassland (mezquital)	MP	half hardy	UK,MX
Pachyphytum hookeri	Sierra Fría, Aguascalientes	2500 m	sun/half shade	*Pinus-Quercus* forest	SMOC	no data	UK,MX

Pachyphytum kimnachii	Cerro Agujón, San Luis Potosí	1800 m	sun/half shade	*Pinus-Quercus* forest	MP	no data	UK,MX
Pachyphytum longifolium	Laguna Meztitlán, Hidalgo	1200 m	sun/half shade	*Pinus-Quercus* forest	SMO	no data	UK,MX
Pachyphytum oviferum	Near Ocampo, San Luis Potosí	1200 m	sun/half shade	N. Grassland (mezquital)	MP	no data	UK,MX
Pachyphytum saltense	El Salto, Monte Escobedo, Zacatecas	1900 m	sun/half shade	Grassland	MP	no data	UK,MX
Pachyphytum viride	North San Juan del Río, Querétaro	1800 m	sun/half shade	Semiarid grassland (mezquital)	MP	no data	UK,MX
Pachyphytum werdermanii	Jaumave, Tamaulipas	700 m	sun/half shade	W. X. scrub -piedmont	SMO	no data	UK,MX
Sedum acroptealum	Barranca San Rafael, San Luis Potosí	no data	sun/half shade	W. X. scrub microfilous	MP	not known in cultivation	Non
Sedum alamosanum	Sierra de los Alamos, Sonora	1065 m	sun/half shade	W. X. scrub microfilous	SMOC	probably hardy, very tiny	Non
Sedum allantoides	Huajapan, Oaxaca	1900 m	sun/half shade	S. X. scrub (sacrocaule)	NMSO	not hardy	MX
Sedum allantoides 'Goldii'	Ixmiquilipan, Hidalgo	no data	sun/half shade	N. Grassland (mezquital)	MP	not hardy	MX
Sedum australe						no data	
Sedum battallae	Near Epazoyucan, Hidalgo	2600 m	sun/half shade	S. X. scrub (sacrocaule)	TVB	not hardy	MX
Sedum bellum	San Ramón, Durango	1900 m	sun/half shade	*Pinus-Quercus* forest	SMOC	not hardy, no for sun exposure	Non
Sedum booleanum	Cerro Blanco, Nuevo León	1340 m	sun/half shade	*Quercus* forest	SMO	no data	??
Sedum bourgaei	Amanalco, Estado de México	2300 m	sun/half shade	*Pinus-Quercus* forest	TVB	not hardy	NON
Sedum caducum	Villa Hidalgo, Tamaulipas	1210 m	sun/half shade	W. X. scrub -piedmont	SMO	not hardy/too tine/too leggy	Non
Sedum calcicola	Rayones, Nuevo León	825 m	Half shade	*Quercus* forest	SMO	not hardy	MX
Sedum carinatifolum	Cadereyta, Querétaro	2350 m	sun/half shade	*Pinus-Juniperus* forest/X. scub	MP	not hardy	MX
Sedum chazaroi	Tolimán, Jalisco	760 m	sun/half shade	Deciduous tropical forest	TVB	not hardy/not much solar exposure	Non
Sedum chrysicaulum	Sierra Peña Nevada, Nuevo León	3400 m	sun/half shade	alpine and subalpine grassland	SMO	slow growing	UK
Sedum clausenii	Victoria, Guanajuato	2300 m	Half shade	*Pinus-Quercus* forest	MP	probably hardy	UK
Sedum clavatum	Tiscalatengo, Estado de Mexico	no data	Half shade	*Pinus-Quercus* forest	TVB	not hardy/not much solar exposure	Non
Sedum cockerelli	Cerro Colorado, Chihuahua	no data	sun/half shade	*Pinus-Quercus* forest	SMOC	might be hardy	UK
Sedum confusum	Chignahuapan, Puebla	no data	no data	S. X. scrub (rossette)		half hardy	UK,MX
Sedum conzattii	Sierra de San Felipe, Oaxaca	no data	sun/half shade	Probably *Pinus* forest	NMSO	have not found	MX
Sedum cormiferum	Near Villa Guerrero, S. of México	no data	sun/half shade	W. X. scrub -piedmont	TVB	biannual	NON

Sedum corynephyllum	Palo Hueco, Hidalgo	1700 m	sun/half shade	S. X. scrub (sacrocaule)	MP	not hardy	MX
Sedum craigii	Cañón del Cobre, Chihuahua	2135 m	sun/half shade	*Pinus-Quercus* forest	SMOC	not hardy	MX
Sedum cupressoides	Near Coxcatlan	2200 m	sun/half shade	*Pinus-Quercus* forest	TVB	hardy but too small	Non
Sedum dendroideum ssp. *prealtum*	Near Río Blanco, Veracruz	no data	sun/half shade	*Pinus-Quercus* forest	SMO	probably hardy	UK,MX
Sedum diffusum	Near Cerro de la Silla,	no data	sun/half shade	S. X. scrub (rossette) and N. Grassland (mezquital)	SMO	no hardy	MX
Sedum ebracteatum ssp.*ebracteatum*	Cadereyta, Querétaro	2200 m	half shade	N. Grassland	MP	not hardy/not much solar exposure	Non
Sedum fructescens	Near Cuernavaca, Morelos	2592 m	sun/half shade	H. X. scrub-pedregal	TVB	not hardy	MX
Sedum furfuraceum	Near Zaragoza, San Luis Potosí	2100 m	sun/half shade	*Pinus-Quercus* forest	MP	not hardy/very tiny and slow growing	Non
Sedum fuscum	Near Calvillo, Aguascalientes	no data	sun/half shade	N. Grassland	MP	not hardy and too tiny slow growing	Non
Sedum glabrum	Near Grutas de García, Nuevo León	no data	sun/half shade	W. X. scrub-piedmont	SMO	not hardy	MX
Sedum goldmanii	Near Tres Marías, Morelos	no data	sun/half shade	*Pinus-Quercus* forest	TVB	too tiny and leggy	Non
Sedum glassi	Victoria, Guanajuato	2300 m	sun/half shade	N. Grassland (mezquital)	MP	Not hardy/new species	MX
Sedum grandipetalum	Near La Bufa, Jalisco	2500 m	sun/half shade	*Pinus-Quercus* forest	SMOC	not hardy, not too much sun	Non
Sedum greggii	Temascalcingo, Estado de México	2400 m	sun/half shade	*Pinus-Quercus* forest	TVB	too tiny	Non
Sedum griseum	Valle de Bravo, Estado de México	aprox 1800	sun/half shade	*Pinus-Quercus* forest	TVB	not hardy	MX
Sedum guadalajarum	Río Blanco, Jalisco	no data	sun/half shade	*Pinus-Quercus* forest	TVB	not hardy, leggy	Non
Sedum gypsophilum	Near Galeana, Nuevo León	2440 m	sun/half shade	*Pinus* forest	SMO	probably hardy, but not pretty	Non
Sedum hemsleyanum	Near Villa Guerrero, Estado de México	aprox. 1880 m	sun/half shade	W. X. scrub-piedmont	TVB	not hardy, not so much sun	Non
Sedum hernandezii	Sierra Negra, Puebla	2400 m	sun/half shade	*Quercus-Pinus* forest	TVB	probably hardy	UK,MX
Sedum hintonorium	Zaragoza, Nuevo León	2085 m	sun/half shade	*Quercus-Pinus* forest	SMO	probably hardy but ugly	Non
Sedum hultenii	Near Texcapa, Puebla	1300 m	sun/half shade	*Quercus-Pinus* forest	SMO	probably hardy	UK
Sedum humifusum	Near Ixmiquilpan, Hidalgo	1650 m	sun/half shade	N. Grassland (mezquital)	MP	too tiny	Non
Sedum jaliscanum	Near Guadalajara	1300 m	sun/half shade	*Pinus* forest	TVB	too tiny	Non
Sedum jurgenensii v. *alongata*	Jacala, Hidalgo	1650 m	sun/half shade	*Quercus-Pinus* forest	TVB	little bit leggy	MX

Sedum kimanchii (decumbens)						Previously sedum decumbens	
Sedum latifilamentum	Near Pinal de Amoles Queretaro	2590 m	sun/half shade	*Quercus-Pinus* forest	MP	Too leggy	Non
Sedum lenophylloides	Tamaulipas y N. L.	no data	no data	no data	SMO	not hardy	Non
Sedum liebmannianum	Tepeaca, Puebla	2300 m	sun/half shade	*Quercus-Pinus* forest	TVB	Too tiny	Non
Sedum longipies ssp. *longipies*	Tlalmanalco, Estado de México	2700	sun/half shade	Grassland	TVB	not hardy/too tiny	Non
Sedum lucidum	Near Orizaba, Veracruz	no data	sun/half shade	*Quercus-Pinus* forest	TVB	probably hardy	UK,MX
Sedum lumholtzii	Tepoca, Sonora	675 m	sun/half shade	*Quercus* forest	SMOC	probably hardy	MX
Sedum macdonaldii	Cerro Potosí, Nuevo León	3500 m	sun/half shade	*Pinus* forest	SMO	probably hardy	UK
Sedum madrense	Oteros River, near Creel, Chihuahua	2270 m	sun/half shade	*Quercus-Pinus* forest	SMOC	too tiny	UK
Sedum mellitulum	Cusarare Falls, Near Creel, Chihuahua	no data	sun/half shade	*Quercus-Pinus* forest	SMOC	too tiny/ probably hardy	UK
Sedum mexicanum	No data	no data	half shade	no data	no data	half hardy	UK,MX
Sdum meyranianum	Near Guadalajara, Jalisco	1680 m	sun/half shade	*Quercus-Pinus* forest	TVB	biannual	Non
Sedum minumum ssp. *delicatum*	Iztaccihuatl, Estado de México	4000 m	sun/half shade	alpine and subalpine grassland	TVB	to tiny/ hibernates	UK
Sedum mocianianum	Acambaro, Guanajuato	2400 m	shade	Deciduous tropical forest	MP	not hardy, not too much sun	Non
Sedum moranense ssp. *moranense*	Near las Vigas, Veracruz	no data	sun/half shade	*Quercus-Pinus* forest	TVB	probably hardy	UK
Sedum muscoideum	Concepción, Pápalo, Oaxaca	no data	sun/half shade	Deciduous tropical forest	NMSO	too tiny	Non
Sedum nanifolium	Chojo Grande, Near Saltillo	no data	sun/half shade	W. X. scrub-chaparral	MP	too tiny	Non
Sedum neovolcanicum	Nevado de Colima	2650-3250 m	Half shade	*Pinus-Abies* forest	TVB	not much solar exposure	Non
Sedum nieum	San Pedro Martir, B. C. N.	2834 m	no data	no data	MSBC	no data	UK
Sedum oaxacanum	Cerro de la Yerba, Puebla	no data	no data	Deciduous tropical forest / *Quercus-Pinus* forest	SMNO/TVB	not hardy	MX
Sedum obcordatum	Barranco Del Alto Pixquiac, Perote,Ver.	nodata	sun/half shade	*Pinus* forest	TVB	probably hardy	UK
Sedum ocuilense	Near Ocuitlan, Estado de México	2100 m	sun/half shade	*Quercus-Pinus* forest	TVB	not hardy/not much solar exposure	Non
Sedum oteroi	Sierra Mixtea, near San Miguel Aztatla	non	sun/half shade	Deciduous tropical forest	SMNO	not hardy	MX
Sedum oxycoccoides	San Juan Capistrano, Valparaiso, Zac.	non	sun/half shade	Deciduous tropical forest / N. Grassland	SMOC	not hardy	MX
Sedum oxypetalum	Pedregal, México, D.F.	2500 m	sun/half shade	H. X. scrub-pedregal	TVB	not hardy	MX

Sedum pacense	San Luis de la Paz, Guanaujuato	no data	no data	N. Grassland	MP	not hardy	MX
Sedum pachyphyllum	Near San Luis Atolotitlan, in Oaxaca	1800 – 2100 m	sun/half shade	Deciduous tropical forest	SMNO	not hardy	MX
Sedum palmeri	Galeana Nuevo León	1600 m	sun/half shade	S. X. scrub (rossette)	SMO	perhaps hardy	UK
Sedum palmeri ssp. *emarginatum*	Peña del aire, near hueyapan, Hidalgo	1960 m	sun/half shade	*Quercus-Pinus* forest	TVB	perhaps hardy	UK,MX
Sedum palmeri ssp. *rubromarginatum*	El rachito, near Villa de Zaragoza, SLP	2100 m	sun/half shade	S. X. scrub (sacrocaule)	MP	perhaps hardy	UK,MX
Sedum papillicaulum	Sierra Peña Nevada, Nuevo León	3000 m	sun/half shade	Pinus-Abies forest	SMO	perhaps hardy	UK
Sedum parvum	Near Puerto Altamira, SLP	2000-2700 m	sun/half shade	*Pinus-Abies* forest	MP	perhaps hardy	UK
Sedum pentastamineum	R.Tiscalatengo, near Villa Guerrero, E.de M.	2340 m	sun/half shade	*Quercus-Pinus* forest	TVB	perhaps hardy	UK
Sedum perezdelarosae	Ixtacamaxtitlán, Puebla	2348 m	sun/half shade	S. X. scrub (rossette)	TVB	not hardy	MX
Sedum quevae	Road from Cuernavaca to Tepoztlán, Morelos	no data	sun/half shade	Deciduous tropical forest	TVB	not hardy	MX
Sedum raramuri	Basihuare, Chihuahua	2000 m	sun/half shade	*Quercus-Pinus* forest	SMOC	not hardy/too tiny	Non
Sedum reptans	Cerro Agujón, SLP	1700 m	sun/half shade	*Quercus-Pinus* forest	MP	probably hardy	UK,MX
Sedum retusum	Cierra de Alvarez , SLP	2250 m	sun/half shade	*Quercus* forest	MP	not hardy	MX
Sedum rhodocarpum	Near Villa Santiago, Nuevo León	650 m	sun/half shade	*Quercus* forest	SMO	not found	Non
Sedum roberti	Near Ciudad Guzman, Jalisco	no data	sun/half shade	*Quercus* forest	TVB	moist environment	Non
Sedum scopulinum	Near Tepeaca, Puebla	no data	sun/half shade	*Quercus-Pinus* forest	TVB	not hardy	MX
Sedum semiteres	Near Topia	1116 m	sun/half shade	*Quercus-Pinus* forest	SMOC	not hardy/not much solar exposure	Non
Sedum spathulisepalum	Near la Fraguita, San Dimas, Durango	no data	shade	Deciduous tropical forest	SMOC	not hardy/not much solar exposure	Non
Sedum stahlii	Cumbres de Alcutzingo Veracruz	no data	sun	S. X. scrub (rossette)	TVB	almost hardy	UK,MX
Sedum stelliforme	Los Altares, Santiago Papasquiaro, Durango	2440 m	sun/half shade	N. Grassland	SMOC	not hardy/too tiny	Non
Sedum suaveolens	Topia, Durango	1158 m	sun/half shade	*Quercus-Pinus* forest	SMOC	not hardy/not much solar exposure	Non
Sedum tehuaztlense	Tehuaztepec, Estado de México	2350 m	half shade	*Quercus-Pinus* forest	TVB	not hardy/not much solar exposure	Non
Sedum tortuosum	Tiscaltengo river, Tenancingo, E.	no data	sun/half shade	*Quercus-Pinus* forest	SMNO	not hardy/difficult propagation/epiphyte	Non

	de México						
Sedum torulosum	Tejupan, Santiago, Oaxaca	no data	sun/half shade	*Quercus-Pinus* forest	TVB	not hardy	MX
Sedum treleasey	Near Atolotitlán, Puebla	2070 m	sun/half shade	Deciduous tropical forest	TVB	decumbent/not hardy when wet	Non
Sedum trichromum	Near Revolcaderos, Durango		sun/half shade	*Quercus-Pinus* forest	SMOC	not hardy/difficult establishment	Non
Sedum versadense var. *versadense*	Near Tenancingo, E. de México?	no data	sun/half shade	Deciduous tropical forest?	SMNO	probably half hardy	UK
Sedum versadense var. *villiadoides*	Near Teotitlán, Oaxaca	no data	sun/half shade	Deciduous tropical forest	SMNO	probably half hardy	UK
Sedum vinicolor	Near el Salto, Oaxaca	2550 m	sun/half shade	*Quercus-Pinus* forest	SMOC	too tiny and slow growing	Non
Sedum wrightii ssp. *wrightii*	San José de Raíces, Nuevo León	1859 m	half shade	S. X. scrub (rossette)	SMO	not hardy/not much solar exposure	Non
Sedum × *amecamecanum*	Iztaccihuatl, Estado de México	2500 to 4000 m	half shade	*Quercus-Pinus* forest	TVB	half-hardy/not much solar exposure	Non
Sedum x *'green rose'*	not known hyb. S. obcordatum & S. palmeri	no data	sun/half shade	not known	non	half-hardy	UK
Sedum x *rubrotinctum*	Garden hybrid S. stahlii and S. pachyphyllum	no data	sun/half shade	non	non	half-hardy	MX
Sedum 'rockery challenger'	S.x luteoviride and Sedum reptans	no data	sun/half shade	non	non	probably hardy	UK
Sedum 'spiral stairs'	Probably S. moranens and somethingelse	no data	sun/half shade	non	non	probably hardy	UK
x *Graptoverya* 'aucalis'	Graptopetalum paraguayense x Echeveria amoena	no data	sun/half shade	non	non	probably hardy	UK

Appendix I. Potential species for green roofs in Climate Cwb and Cfb based on (Almeida et al., 1994, Bischofberger 2010, Burquez et al., 1998, Canizales-Velázquez et al., 2009, Castillo-Argüero et al., 2004, Clausen, 1959, Eggli, 2003, Etter and Kristen, 1997, Evans, 1962, Evans, 1983, García-Morales, 2013, González-Medrano, 2004, Hágsater et al., 2005, INEGI, 2011b, INEGI, 2011a, Kimnach Myron, 1986, Leopold, 1950, Low, 2008, Low, 2007a, Low, 2007b, Low, 2007c, McDonald, 1990, Meyrán-García, 2003, Miranda and Hernández, 1963, Pilbeam, 2008, Praeger, 1921, Rzedowski et al., 2010, Rzedowski, 1986, Sánchez-Del Pino et al., 1999, Stephenson, 1994, Stromberg, 1993, t'Hart, 1997, Thiede and Eggli, 2007, Véliz-Pérez and García-Mendoza, 2011, Walther, 1952). In the column observations the hardiness report for *Sedum, Graptopetalum* and *Graptoveria* are reports from Ray Stephenson for Northumberland, UK. *Echeveria* species hardiness based on reports by Pilbeam for the UK. Non data on any column means it was not found on records, in literature or in first descriptions of the plant species.

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