Native Plant Mixtures for Atlantic Canada Green Roofs: Compatibility with *Sedum*s, Propagation Techniques and Soil Design.

By

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Abstract

In Atlantic Canada, there has been a significant amount of research on green roofs including ecosystem services and native plant selection. This project examines a few remaining gaps in the research: lack of locally available growth media, the feasibility of combining native plants with *Sedum* in the same system, and optimal propagation techniques for native species. Plant growth and performance of ecosystem functions were examined with the combinations in a replicated modular green roof system. The most beneficial treatment was a mixture of native plants/*Sedum*s planted as plugs in the commercially available growth medium. Moreover, plug planting was the most effective way to quickly establish plant canopy density in this green roof system. This project is expected to facilitate the use of native plants on green roofs to diversify the plant selection available while also outlining the most effective techniques and growth media at a cheaper cost.

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Chapter 1: General Introduction

Green roofs, consisting of vegetation and substrate on top of urban infrastructure, provide benefits to ecosystems in urban areas as vegetated areas become depleted and replaced with impervious surfaces (MacIvor and Lundholm, 2011). Some benefits include ecosystem services like: improved stormwater retention, reduced urban heat island effects, and habitat for wildlife (Oberndorfer et al., 2007). Generally, there are two different types of green roofs: extensive and intensive green roofs (Kotze et al., 2020). Extensive green roofs are characterized by shallow substrate depths (4 to 20 cm) (FLL, 2002), low organic matter in growth media (65 g/l) (FLL, 2002) and vegetation well suited to coping with extreme xeric conditions such as *Sedum* species (FLL, 2002). Intensive green roofs typically have substrate depths of 15 to 200 cm, 90 g/l organic matter and perennials, grasses, bulbs and shrubs (FLL, 2002). Often, the term substrate and growth media are used interchangeably in green roof terminology.

There are few green roofs in Atlantic Canada compared to large cities like Toronto; however, their implementation is expected to grow in the coming years. As of November 30th, 2019, Halifax Regional Municipality (HRM) developed and passed a By-law titled Regional Centre Land Use By-law for the city of Halifax and downtown Dartmouth. This by-law will enforce the development and construction of green roofs within the cities. Halifax and Dartmouth will likely benefit from this new legislation as stormwater accumulation and reduction of pollinator communities continue to be a threat to these areas.

Urban areas have many impervious surfaces in the form of buildings and parking lots, which take the place of porous, vegetated areas. Therefore, stormwater can accumulate on the surface and run off, posing a serious threat to ecosystems and urban area living. Green roofs are known to retain water and delay peak flow and are therefore able to reduce these risks (Mentens et al., 2006). As rainwater enters a green roof system, water is absorbed by pore spaces within the growth medium, organic matter, and by vegetation (Vijayaraghavan, 2016). A reduction of available habitat has also taken place (Colla et al., 2009; Falkner, 2003; Xu et al., 2018) in urban areas. Ecologists have been slow to acknowledge urban areas as viable options for wildlife habitats such as those for important pollinators, insects and birds (Lundholm, 2006); alternative habitats in urban settings may be important for the sustainability of native ecosystems and requires a diverse and abundant supply of bees (Cane and Tepedino, 2001).

The HRM is the largest city in Atlantic Canada and the Capital of Nova Scotia. It spans approximately 5,500 square kilometres and had a population of approximately 440,332 in 2019 (Statistics Canada, 2019). Halifax's current stormwater system includes a mix of ditches and culverts, combined sewers, separate storm sewers, street curbs and gutters, and retention ponds or tanks (Sheppard, 2012; Cranstone et al., 2015). During heavy rainfall, not all water enters these systems and stormwater accumulates on impervious surfaces (Sheppard, 2012). Negative impacts can be felt across the whole city through damages to water courses, erosion, reduced water quality and flooding of properties. Leakage of stormwater into the wastewater system (Cranstone et al., 2015) may be particularly detrimental to Halifax as a heavy storm can increase the system flow up to 25 times, thus resulting in sewage overflows and other toxic wastes putting human health at risk (Sheppard, 2012). To mitigate against this, evidence shows that the selection of plants and growth media optimal for the retention of stormwater on green roofs should be considered (Orberndorfer et al., 2007). Regarding the protection of pollinator communities in the

HRM, floral display and floral richness were the strongest predictors of pollinator richness and abundance on green roofs (Grimshaw-Surette, 2020). With the variety of plants able to survive on green roofs, wildlife will have a larger chance of survival on the roof.

There are numerous aspects involved in the construction of a green roof including construction, roof integrity, plant selection, propagation selection, soil growth media composition, and costs (monetary and time). Germany, known as a world leader in green roof technology, have documented techniques regarding these aspects in a detailed guideline for green roof users called the FLL guidelines (Orberndorfer et al., 2007). These techniques are also considered a source of authority with respect to green roof construction in North America as well as other areas of the world (Dvorak and Volder, 2010) since there are no well-defined or recognized guidelines in these regions.

Species selection recommendations in these guidelines have been carefully researched to ensure plant survival on green roofs. Other studies found that species that can survive characteristics in their natural habitat like shallow substrate depth and full exposure to the environment (Lundholm et al., 2010) can be good choices for green roof plants. Extensive green roofs are designed for a functional purpose rather than aesthetics as they ultimately require less maintenance (Oberdorfer et al., 2007). Therefore, due to shallow substrate depths on extensive green roofs (ranging from 2 to 15 cm), *Sedum* species are often used as they often outperform other taxa (Oberndofer et al., 2007). *Sedum*s are drought-tolerant succulents that are very commonly planted as the main vegetation on extensive green roofs, but there are no *Sedum*s native to eastern Canada. In recent years, North American native taxa have been observed to have potential for use on green roofs due to their adaptation to the existing local climate (Monterusso et al., 2005; Lundholm et al., 2010; Butler et al., 2012; Aloisio et al., 2019). Native stress-tolerant plants from dry grassland, coastal and alpine heathlands offer opportunities for green roofs (Oberndofer et al., 2007). Additionally, moss and lichen species also have potential for improving the functions and ecosystem services on green roofs as they may also provide benefits like reduced growth media temperatures. Green roofs are often low in plant diversity, therefore Lundholm, (2015) suggests that adding mixtures of plant species to green roofs can increase provision of ecosystem services and can be achieved by determining what plant mixes work best together.

Growth media composition is also an important consideration when installing a green roof. Green roof growing media are not composed of the same materials used for houseplants, container gardens or even bioretention cells; they are often specifically designed for green roof vegetation and environmental characteristics. Design criteria for green roof growth media include: adequate water retention, proper porosity, and sufficient nutrients but not excess nutrients that result in high leaching rates (Toronto and Region Conservation Authority, 2016). Guidelines are an important tool for user reference due to the large number of considerations on green roof installments.

Various studies have been conducted on green roofs in Halifax regarding the use of native plants on green roofs, pollinator communities, insect diversity, and nutrient concentrations in runoff water. However, a few areas lack research like a mixture of native plants with *Sedum*, moss and lichen. Additionally, a well-defined green roof guideline to help users would be beneficial proceeding the implementation of the new Regional Center Land Use By-Law in Halifax and Dartmouth. In this study I will evaluate top performing native plant species from Atlantic Canada while also quantifying the costs and benefits of different treatments and propagation techniques on green roofs. I will compose a document outlining protocols for the inclusion of native species on green roofs, with comparisons of different options in monetary and time costs. This will be completed with respect to propagation techniques, growth media composition and the addition of lichen and moss and *Sedum* species. My goal is to compare these different combinations so that building owners, plant nurseries, landscape architects and other researchers will have proper guidance for effective green roof instalment in Atlantic Canada. Indicators of green roof benefits, such as substrate temperature and water retention, will also be recorded to test the effectiveness of each treatment. The main research question to investigated is: what treatment combination did best (monetary and time) with respect to plant growth (canopy density and plant height), water retention, growth media temperature and floral display. In-depth analysis of propagation technique, growth media choice and plant mixtures are investigated. Developing protocols and how-to documents regarding this important information are an essential tool for the mass implementation of green roofs in Germany and should be used as an example for other areas globally.

The following review of literature will give an in-depth overview of green roof history, the importance of protocols, plant selection and optimal mixing, growth media composition and propagation techniques used on green roofs. Following this, gaps in literature are discussed regarding green roof technology in Atlantic Canada that will further explain the importance of research in these areas.

Chapter 2: Review of Literature

2.1 Green Roof History

At the turn of the 20^{th} century, modern green roof technology quickly escalated in Germany. Formulations of progressive environmental policy and technology were introduced as environmental concern increased with knowledge of climate change (Oberndorfer et al., 2007).

Germany embraced green roof technology due to the broad-ranging environmental benefits (Dvorak and Volder, 2010). Upon completion of the first-generation roofs in the 1970s, waterproof membranes showed signs of damage. Techniques were then documented, and materials were developed to respond to building design issues to continue the development of green roof technology (Oberndorfer et al., 2007).

Early green roofs were typically designed as intensive green roofs where they were characterized for their deep substrates with a variety of plantings and also had the appearance of conventional ground-level gardens (Oberndorfer et al., 2007). After research and development had gone into green roof design, demand for the newly coined "extensive" green roofs became more prominent. This meant that instead of having highly maintained gardens with diverse vegetation, green roof consumers could have self-maintaining species indefinitely (Ngan, 2004) including grasses, moss, lichens, and succulents (Vijayaraghavan, 2016). These self-maintaining species can survive in a thin growth medium (Vijayaraghavan, 2016). However, species intended to be planted on extensive green roofs must be carefully selected due to difficult growing conditions. This includes characteristics like shallow substrate depth, high winds and full insolation (Lundholm et al., 2010).

In 1975, members of the German Landscape Research, Development and Construction Society developed a set of guidelines for green roofs known as the FLL (Forschungsgesellschaft Landschaftsentwicklung Landschaftsbau) Guidelines. The guidelines are used for green roof design, specification, maintenance and testing (FLL, 2002; Dvorak and Volder, 2010) and are based on findings from empirical green roof research and application throughout Germany. In 2002, the guidelines were published in English and recognize rules of techniques.

2.2 Optimal Plant Species and Mixtures for Green Roofs

Several documents have been produced that outline design characteristics for green roofs including determination of structural loads, permeability tests for drainage in substrate and a guide for selecting and maintain plant material (ASTM E 2400, 2006). Although these documents exist, there is no well-established guidance on their application in North America (Miller and Narejo, 2005; Dvorak and Volder, 2010). The FLL Guidelines outline significant coverage dedicated to the design and specification of substrates and vegetation since these selections are important for a successful green roof (Dvorak and Volder, 2010).

Rooftop conditions can be challenging for plant survival and growth. Factors affecting plant survival include drought, moisture, temperatures, high light intensity, and high winds with the risk of physical damage (Dunnett and Kingsbury, 2004). Stress-tolerant characteristics such as low, mat-forming growth, evergreen foliage, succulent leaves, and good water storage capabilities (by the use of CAM) (crassulacean acid metabolism)) (Lee and Kim, 1994) are often selected for. For this reason, the most common species on green roofs are *Sedum* species. *Sedum* species exhibit CAM photosynthesis, allowing them to conserve water by conducting most of their gas exchange in the cool night atmosphere (West-Eberhard et al., 2011).

Native plants also provide benefits that *Sedums* do not, like augmenting resources for pollinators such as bees that are at risk from habitat destruction and urbanization (McDonald et al., 2008; Winfree et al., 2009). However, some native plants may be unsuitable for conventional extensive green roofs due to the harsh roof environments and shallow substrate depths (Oberndofer et al., 2007). Studies show treatments that included native lichens and mosses also reduced growth media temperatures, which is important for reducing the urban heat island in urban areas (Heim and Lundholm, 2014). Moreover, Heim and Lundholm (2014) also concluded the native Nova Scotia plant species, *Festuca rubra*, performed significantly better when planted with mosses during drought and still reduced growth media temperatures. If green roofs installations are to be successful in the wide range of climatic conditions present across the globe, then a better understanding of what specific taxa will survive and thrive in those geographic locations is needed (Monterusso et al., 2005). Therefore, understanding and conducting studies on optimal mixing of natives, *Sedum* and moss and lichen taxa may be useful for the success of green roof systems.

Because extensive green roofs typically rely on *Sedum* monocultures or low diversity plant communities, MacIvor and Lundholm (2011) identified ten strongly performing native plant species in Atlantic Canada on green roofs. These included *Danthonia spicata*, *Festuca rubra*, *Solidgo bicolor* and three industry-standard *Sedum* species that achieved almost 100% survival after three growing seasons on an extensive green roof at Saint Mary's University, Halifax. However, the combination of natives and *Sedum*s has not yet been extensively researched, and use of native species on green roofs is not yet common in the region. Some possible reasons why natives are not commonly used in Atlantic Canada include: unavailability of native plant species appropriate for extensive green roofs in local nurseries, low knowledge of propagation techniques for native species, landscape designers being unaware of the benefits of native plants, and the green roof industry's preference for drought tolerant *Sedums*.

2.3 Important Ecosystem Services to Atlantic Canada

Finding appropriate benefits to select for is also crucial when considering the construction of a green roof (Oberndorfer et al., 2007). Green roofs in Atlantic Canada may provide beneficial stormwater retention and pollinator habitat creation for the region. However, other services, such as energy conservation and moderation of the urban heat island, are less beneficial to the area or may lack support from empirical research.

Thermal benefits of green roofs during hot seasons are well characterized in many areas (Oberndorfer et al., 2007; Clark et al., 2008; Saiz et al., 2006). However, for cold seasons, modelling studies predict less significant reductions in heat flow out of buildings under green roofs compared with conventional roofs (Eumorfopoulou and Avarantinos, 1998; Sailor, 2008; Jaffal et al., 2012). Very few studies of green roofs indicate a reduction of thermal energy in colder months resulting in saved energy (Lundholm et al., 2014). Because Atlantic Canada has a long cold season compared to warm seasons, it may not be beneficial for Atlantic Canada to focus on energy savings as a driver of green roof implementation.

A study conducted by Lundholm et al., (2014) in Halifax, Nova Scotia quantified heat flux, substrate temperature and snow depth and determined relationships between vegetation type, snow accumulation and substrate temperature. Overall, they found that the benefits of green relative to conventional roofs were lower in extreme winter conditions when the substrate was frozen or had snow cover, but also during sunny conditions. This suggests that thermal benefits in winter are unlikely to be significant in Nova Scotia, relative to the cost of installing and maintaining green roofs. In general, even summers in Halifax, Nova Scotia are relatively cool with an average of 18.9 °C in August, the warmest month (Environment Canada, 2021). However, studies project that there will be an increase in temperature during the summer months for Nova Scotia (Whitman et al., 2014) as global warming increases. Therefore, energy conservation from green roof installation could be beneficial in future summer months.

2.3.1 Stormwater Retention

Some consider stormwater retention to be the greatest environmental service that green roofs provide (Getter et al., 2007). As green roofs increase in popularity it is important to note that some aspects receive more attention than others, for example, the quantity of water collected and the amount of retention observed rather than the quality of the runoff water (Berndtsson et al., 2009). More research should be conducted on the lesser-known benefits provided by stormwater retention. This will allow for better designs and services provided in the future.

Historically, green roof vegetation originates from cool climates thus posing challenges for temperate or warm climates (Vanuytrecht et al., 2014). Some challenges the vegetation from cooler climates may face include the inability to adapt to dry periods, extreme temperatures or even extended wet periods (Vanuytrecht et al., 2014). Vanuytrecht et al., (2014) assessed vegetation drought stress and runoff quantities for different green roof types (grass, herb and *Sedum* vegetation). The grass and herb species were found to reduce runoff more than *Sedum*-moss green roofs but were more sensitive to increased drought. This study importantly indicates that each region should have tailored vegetation with the incorporation of native species.

MacIvor and Lundholm (2011) experimented with various native species to Nova Scotia, Canada including graminoids, tall forbs, and creeping shrubs to evaluate their performance for stormwater retention. Many of the locally occurring species showed equivalent or improved performance for some or all of the green roof services compared to only growing medium controls and conventional roof surfaces. Some of the species used even outperformed the common green roof *Sedum* species. Specifically, native grass species performed well with high transpiration rates and above-ground biomass cover which in turn contributed to roof cooling. This proved effective at taking in large amounts of water further confirming their ranking as the top species for water capture (Dunnett and Kingsbury, 2010). Species that can absorb more water from substrates will create more space for water capture in other rain events, however, they may exacerbate impending drought conditions on the roof (MacIvor and Lundholm, 2011). MacIvor and Lundholm (2011) indicate one *Sedum* species, *S. acre*, had excellent cover and resulted in low roof surface temperatures compared to other monocultures, but had relatively low stormwater capture. Mixing this *Sedum* species with some of the better performing native grasses could create a mixture that provides both ecosystem services of cooler temperatures and better water retention.

2.3.2 Pollinator and Wildlife Habitat

Very few recent studies document the habitat value of green roofs, such as those providing shelter for numerous organisms (Madre et al., 2013). This may be due to the perception that urban areas are too disturbed to support species of conservation concern (McDonnell et al., 1997).

Bees (Hymenoptera: Apoidea) are an important group of organisms for the ecosystem service of pollination (Bond, 1994; Allen-Wardell et al., 1998; Vamosi et al., 2006; Klein et al., 2006). There have been substantial declines in both wild and managed bees in North America, attributed to habitat loss, pesticide use, global warming, diseases, and competition with introduced species (Berenbaum et al., 2007). Studies show that a variety of native bee species can use green roofs as foraging and/or nest building habitat and that there is a degree of overlap in bee communities between green roofs and nearby ground level sites (Colla et al., 2009). Although the number of species found was lower than that known for non-urban habitats, green roofs can offset some of the pressures threatening bee populations (Colla et al., 2009).

Increasing plant diversity to increase species diversity is also important. Madre et al., (2013) found that species richness and the abundance of most arthropod taxa were significantly higher on roofs that displayed more complex vegetation and were comprised of xero-thermophilic species and species from sandy/rocky habitats. Investigations such as those conducted by Lundholm et al., (2010) showed that 200 insect species, including over 50 species of beetles, were found on a green roof. Half of the species were native to the region and investigators attributed the species richness to the age of the substrate and density of the native and non-native flowering plants (Lundholm et al., 2010; Dvorak and

Volder, 2010). Bees are presumed to benefit more from green roofs than other insect species due to their high mobility in search of flowers and can search for pollen vertically between green roofs and ground level (Braaker et al., 2014).

As research suggests, bees are in decline worldwide (Potts et al., 2010) but they are the most significant pollinators in urban areas (Theodorou et al., 2020). Pollination is a crucial ecosystem function in terrestrial systems thus increasing the ability for pollinators to survive in urban areas is important (Robinson and Lundholm, 2012). Creating pollinator-friendly habitats helps maintain populations of pollinator species (Oberndorfer et al., 2007). that may otherwise be unable to provide their important ecosystem services.

2.4 Propagation Techniques and Soil Design for Green Roofs

Soil composition varies from place to place, but generally includes minerals, water, organic material and air (Foth, 2003). The profile of a soil develops thousands of years and occurs as minerals and organic matter break down caused by weathering (North and Agro, 2020; Kalev and Toor, 2018). A soil profile typically consists of organic material, topsoil, subsoil, weathered rock and rock (Kalev and Toor, 2018). Composition and soil biodiversity determines the nutrients available to plants such as magnesium and potassium, as well as the moisture available to them (Strahm and Harrison, 2008). Roughly one gram of soil contains up to one billion bacteria cells, 200 million fungal hyphae, a wide range of mites, nematodes and arthropods (Roesch et al. 2007; Bardgett, 2005). This large amount of soil diversity and soil composition greatly impacts and contributes to the above-ground terrestrial biodiversity (Fierer et al., 2009; Wardle et al. 2004).

In recent years, urbanization has been shown to drastically impact the physical and chemical properties of soils (Pavao-Zuckerman and Coleman, 2007; Pickett et al., 2001). Urban soils typically have a normal or natural topsoil but altered lower profile. Layers are often added and modified to add elevation in urban areas (North and Agro, 2020), which can lead to contamination as backfill occurs on construction sites. This disturbance may reduce microbial abundance and the overall diversity of organisms in the soil (Helgason et al., 1998; de Vries et al., 2013). Cycling of resources between communities in the soil and the biodiversity of plant communities may also be reduced (Wagg et al. 2013).

Urban expansion will continue to affect soil composition, water resources and water quality of natural landscapes (USEPA, 2001; Ahiablame et al., 2012). The increased use of low impact development (LID) projects may improve negative effects associated with these disturbances; it is necessary to develop specific soil blends tailored for each LID project to reduce the negative impacts associated with urbanization. Challenges regarding LID projects include examples like creating engineered soil to ensures plant establishment and success, but also meets the objective of the project (i.e., rapid infiltration).

Important characteristics for designing green roof soil includes the possession of chemical, physical and biological features necessary for supporting the vegetation, stable structure for anchorage of plants' root systems, balanced water permeability, retention and drainage as well as basic nutrients and optimum air management (North and Agro, 2020).

Traditional container gardening media are high in organic matter. With time and repeated rains, the organic matter tends to break down, decreasing the volume of soil and lowering aeration for plants (Ritchie and Dolling, 1985). In order to ensure a prolonged lifespan to green roofs, the growing medium is typically composed of mineral aggregates and only a small percentage of organic material (Toronto and Region Conservation Authority, 2016). This helps prevent the roof from losing too much soil volume over time. While organic matter limits are important, there also needs to be enough organic material to supply nutrients to the plants on the green roof.

While most green roof studies consider stormwater retention, the quality of runoff has received less attention (Van Setters et al., 2009). Conventional roofs are known to result in elevated levels of polycyclic aromatic hydrocarbons, organic halogens and heavy metals in runoff water (Thomas and Greene 1993; Van Metre and Mahler 2003) but green roofs are typically expected to have fewer of these contaminants. However, studies show that nutrients like phosphorus could be a potential concern since the concentration levels in green roof runoff were well above receiving water standards (Hathaway et al., 2008; Hutchinson et al., 2003). So, while reducing metals such as zinc, copper and lead through the use of green roofs is common, there is potential for an increase in nutrient concentrations in runoff water. It is important to consider these high runoff nutrient concentrations because it increases the risk of eutrophication of lakes and receiving waters (Carpenter, 2016). Eutrophication is predominately driven by phosphorus from agricultural practices (Kuoppamäki and Lehvävirta, 2016) and can create issues for other bodies of water like increasing algae blooms. According to the FLL guidelines, nutrient content in growth media should be kept as low as possible. Nitrogen, phosphorus, potassium and magnesium should be kept under 80, 50, 500 and 200 ppm respectively.

Growth media and plant composition play a large role in the water quality of green roof runoff. Plants are capable of reducing pollutant leaching but this depends on their health and structure (Chen and Kang, 2016). Tall stems and dense roots help retain rainwater and soil and therefore, reduce the amount of nutrients in leaching. Studies also show that a diverse plant community can improve the performance of water retention (Dunnett et al., 2008; Lundholm et al., 2010). Effective growth media composition must consider texture, organic content of media, compactness, depth, filters on the roof, and the type of vegetation in the media (Toronto and Region Conservation Authority, 2016). If the grain size of each particle is too large (from aggregates, sand, silt or clay), the water will drain too quickly thus allowing more nutrient leaching to occur.

2.4.1 Designing Green Roof Media

For an optimal green roof medium, the mix should contain the following (based on specifications from Sustainable Technologies Evaluation Program, Toronto and Region Conservation Authority, 2019) (STEP) and the FLL guidelines:

1. Lightweight Aggregate: These include pumice, lava stone or expanded clay aggregate such as haydite. Materials such as these are a good basis for a green roof growing medium as they help to maintain air and water movement through the soil. Aggregates should be fine to medium texture and should not exceed 60% of the media
2. Organic Material: This includes compost, composted bark, bark fines or a blend of all three. The organic matter provides basic nutrients and is able to retain moisture but too much will cause degradation and decrease porosity. The organic content should also be less than or equal to 65g/l. The pH of the media should lie between 6.0 and 8.5.
3. Sand, silt or clay: Sand is required to balance organic matter and assist in soil structure. FLL guidelines indicate that for extensive green roofs, silt and clay

content should not exceed 15% by mass and the largest grain size should not exceed 10 mm. If coarse sand is being used, it should only make up 40% of the media. When vegetation substrates are at full water capacity, the amount of air present should be no less than 10% volume.

Other factors such as the use of certain types of organic matter content and mycorrhizal inoculation also play a role in the retention of water in growth media. Studies show that improved soil structure generally has positive impacts on soil moisture retention (Hamblin, 1985). Some studies show that mycorrhizal influence on soil water relations is due to arbuscular mycorrhiza symbiosis (AM symbiosis), which may impact plant behaviour during drought (Duan et al., 1996). It is possible that AM symbiosis increases the capability of root systems to scavenge water in drier soil (Duan et al., 1996). Moreover, AM fungi have been shown to enhance aggregation in both pot and field experiments (Schreiner and Bethlenfalvay, 1995).

Organic matter, such as peat are known for their water storage capabilities. Peat is typically characterized by a high proportion of small pores and a heterogeneous pore structure (Weiss et al., 1998). There are also different pore categories including large multiple and connected open pores, dead-end pores, isolated pores and pores in the cell structures (Loxham, 1980). This structure elicits a different response from other granular geological porous growth media (Hoag and Price, 1985) thus resulting in larger quantities of water retained.

2.4.2 Propagation Methods for Green Roof Plants

Various vegetation establishment methods may be used on green roofs based on price range and time constraints to achieve the desired vegetation. Comparing these methods when designing a green roof help users determine best management practices based on their needs or constraints.

One establishment method on green roofs includes using seeds that are directly ejected with the growth medium onto the roof. This occurs through blowing the contents out of machinery and is an extremely cost-effective (monetary and time). This method takes around three weeks for germination to occur and in about one-month full coverage may occur (Toronto and Region Conservation Authority, 2016). Depending on when planting occurs, growth may not be maximized until the following growth season.

Cuttings from preexisting plants may also be used where crushed parts of plants (such as those from *Sedum* species) are sprinkled on top of substrate and this usually takes around one full year for establishment. Cuttings are sometimes used for saving money for *Sedum* treatments (Buist, 2020).

Plugs are another method used on green roofs and involve pre-growing a plant in a plant nursery to give an instant green effect after they are installed. This method may sometimes be challenging because they take longer to fill in whereas seeds and cuttings are much more numerous when installation are taking place. It can take up to two years to completely fill in a roof from plugs (Buist, 2020).

Lastly, modular green roof technologies are becoming more and more popular in some countries (Velazquez, 2003). Modular systems have all the benefits of the green roof while addressing the limitations of a built-in system (Hui and Chan, 2008). Modular trays and pre-grown mats are a simple method for establishment as all plants are already grown in media and can be installed in the module or mat they come in (Hui and Chan, 2008). It is important for modular systems to include locking clips, permeable sidewalls and filtered water reservoirs to allow for proper drainage and discourage the trays from separating and causing growth medium and vegetation to fall between the cracks (Buist, 2020). Mats may be a good idea over trays when installing a larger green roof.

2.5 Governance

The governance of mitigation efforts such as the implementation of green roofs is a challenging task due to the complexity of organizations involved (Stamatelos, 2012). Although governments play an important role in the establishment of laws, regulations and environmental protection institutions, there has been a shift associated with the rise of new forms of governance arrangements that involve public as well as private actors (Stamatelos, 2012; Falkner, 2003).

Public and private governance arrangements enable the accumulation of resources like knowledge and expertise between the different parties involved. The inclusion of public governance may also alleviate the possibility of overstretched governments (Stamatelos, 2012).

Stuttgart, Germany, is a great example of the involvement of both public and private governance where the political perspective is present, although not dominant in Stuttgart. Political influence of the Green Party and environmental consciousness of citizens have created a system where public participation is encouraged and sometimes enforced. Citizens are able to provide recommendations and can also object if they disagree with certain points in a plan (Stamatelos, 2012). Financial incentives have also been used to promote the spread of green roof technology in Stuttgart and other cities globally. These include the implementation of stormwater fees where a property owner must pay fees based on the ratio of a property containing impervious surfaces in relation to the total area of the plot. If a green roof is installed, property owners receive a 50% reduction in stormwater fees (Stamatelos, 2012). Currently, this system works well for Germany as they are the top performers in the green roof industry. Although the United States is considered behind in the green roof industry, there have been some recent strides throughout the past decade to improve this (Stamatelos, 2012).

2.6 Governance in Nova Scotia

As of November 30th, 2019, Halifax Regional Municipality developed and passed a By-law titled Regional Centre Land Use By-law for the city of Halifax and downtown Dartmouth. The By-law states that a person shall comply with this By-law when undertaking a development including constructing, altering or reconstructing any structure. In regards to green roofs, the By-law states any building with a flat roof shall provide soft landscaping (substrate with vegetation) on at least 40% of the roof area. The By-law also indicated that where soft landscaping is required, a minimum number of different plant species shall be provided. For example, if the area requires at least 10 trees or shrubs, then at least three different tree or shrub species must be used. This ensures the inclusion of species diversity. Although this new By-law is a step in the right direction, there are still many improvements to be made including implementation in other areas of the province, plant and growth media selection suggestions, maintenance requirements and community involvement.

2.7 Gaps in Green Roof Literature for Atlantic Canada

In Halifax, Nova Scotia, a variety of green roof studies have been conducted over the last 10 years from Saint Mary's University. Studies from the Ecology of Plants in Communities

Lab at Saint Mary's have examined plant selection and function, pollinator communities on green roofs, amendment addition to growth media, insect diversity, and nutrient concentrations in runoff water.

In 2010, one study from this region tested native Nova Scotia plant species and concluded that several of the species had optimal survival although with sizable differences existing between life form groups (MacIvor, 2010). This result was tested and used in various other studies (Grimshaw-Surette, 2016) over the next several years and even include the addition of moss and lichen species to plant mixtures (Heim, 2013). Eventually, a list of native species in Nova Scotia was recognized as doing well on green roofs through the continuous experiments on the different uses for native plant species (floral display, temperature reduction, water retention, etc.).

While the E.P.I.C (Ecology of Plants in Communities) lab had completed extensive green roof research in many different areas detailing optimal green roof mixtures and functions, there is no local green roof growth media blend that would be suitable for the plant mixtures while also performing appropriately for retention, drainage and nutrient levels. A local blend would provide an environmentally friendly option for green roofs that may be constructed from recycled material and avoid increased fossil fuel use from transportation of green roof media from other provinces.

Native plant species may survive and flourish when used in combination with popular green roof *Sedum* species, but, studies regarding these mixtures have not been extensively researched in the Atlantic region. While moss and lichen species have been tested and observed to survive on green roofs (Heim and Lundholm, 2014), they have not yet been combined with native plants and *Sedum* species together. Together, these species may provide optimal benefits while increasing the biodiversity on green roofs.

A final knowledge gap in Atlantic Canada is a concise, how-to protocol that details appropriate plant mixtures, soil combinations and propagation techniques for a variety of users like plant nurseries and landscape architects. Larger cities such as Toronto use a variety of protocols and guidelines including those created by Sustainable Technologies and Toronto and Region Conservation Authority, and outline methods. However, their selections are not tailored for the Atlantic Region. Due to the recent implementation of the green roof by-law in Halifax, a protocol such as this would be beneficial as it would include extensive research already done in the region.

2.8 Objectives of Study

My first objective was to determine the best installation method for plant growth. Two establishment methods were tested: direct seedings vs. plug planting. Time and financial budgets were recorded to determine effectiveness of plant growth relative to costs in time and money. These two methods are important to consider as green roof users often want to maximize the survival of the plants while also maximizing the speed at which high plant cover is achieved.

For my second objective, I incorporate *Sedum* species into a native plant mixture as they can have superior survival in low growth media levels (as low as 2 to 3 cm) (Oberndorfer et al., 2008). When combined with native plant species they may increase ecosystem service provisioning and biodiversity (Lundholm, 2015). *Sedums* have been used on green roofs for their ability to adapt to dry environments, almost year-round coverage, availability and easy propagation (Nagase and Dunnett, 2010). However, with the inclusion of natives already adapted to the climatic region they are found (Orbendorfer et al., 2007), benefits were expected through increased biodiversity.

Objective number three involves adding moss/lichen species into specific treatment combinations to examine their performance with other native plants and *Sedum* species. Moss and lichen species spontaneously colonize both traditional and green roofs in many parts of the world (Studlar and Peck, 2009; Emilsson, 2008; Heim et al. 2014) which is an indication that they can survive harsh green roof environments.

My last objective was to formulate my own growth media based on the FLL guidelines from recycled or locally sourced material to be used as an option for green roof installment in Nova Scotia. In Nova Scotia, growth media for green roofs comes primarily from Quebec, Canada from SOPREMA Inc. They produce a product called Sopraflor X™, which is a growth medium formulated according to the requirements of the German FLL guidelines for non-irrigated and low maintenance green roof systems (SOPREMA Inc., Lachance Quebec, Quebec). If the locally formulated growth medium is comparable to Sopraflor X, it would provide an environmentally friendly option at a cheaper cost by using recycled materials such as crushed brick and compost from waste facilities.

Results from this project will be directly useful to a range of user groups. My strategy is to develop a how-to protocol that can be published as a brochure, allowing nurseries, green roof companies, landscape architects, researchers and other users to easily access and assess options for incorporating propagation techniques, native plants and mixtures, moss and lichens and locally sourced growth media onto green roof projects in Atlantic Canada.

Chapter 3: Materials and Methods

3.1 Roof Set-up and Modular System

This study took place between September 2019 to September 2020 and was conducted on the library green roof (study block one) and atrium green roof (study blocks two and three) at Saint Mary's University in Halifax, Nova Scotia. (44°39'N, 63°35'W) (Figure 1). A modular green roof system was used and consisted of 36 cm x 36 cm x 12 cm trays (known as modules) (Figure 3) with holes in the bottom to allow for proper drainage (Anderson Die-Deep Propagation Flat; Stuewe and Sons, Tangent, OR, USA). Contained within each module was a water-retention mat fitted at the base including a plastic webbing over a root barrier (Huesker, Charlotte, NC, USA) (Figure 2).

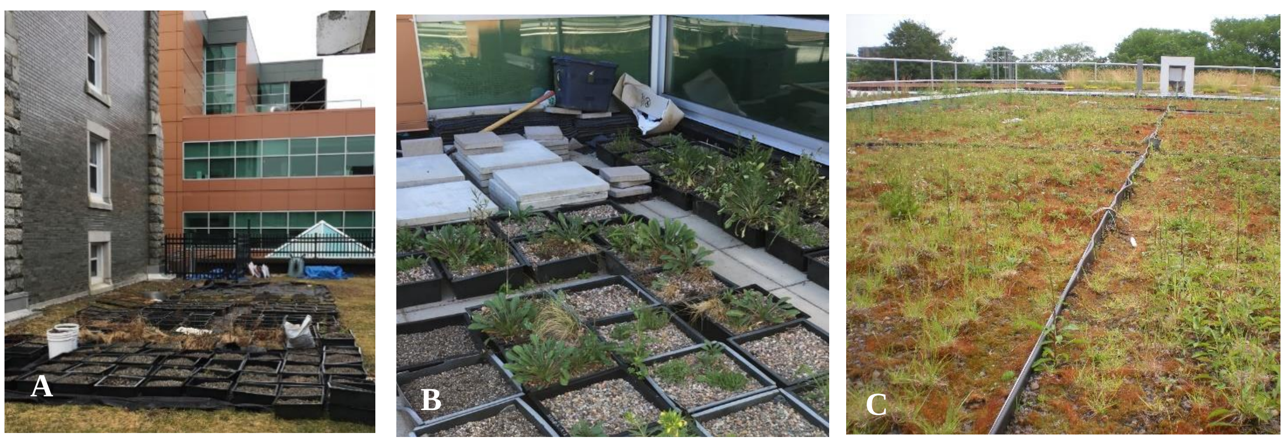


Figure 1. Images of the three study blocks used in this study. Study block 1 (A) occurred on the library roof at Saint Mary's University which was almost entirely surrounded by walls while study block two (B) and three (C) occurred on the atrium roof where block two was partially surrounded by wall and block three was complete exposed to the elements.

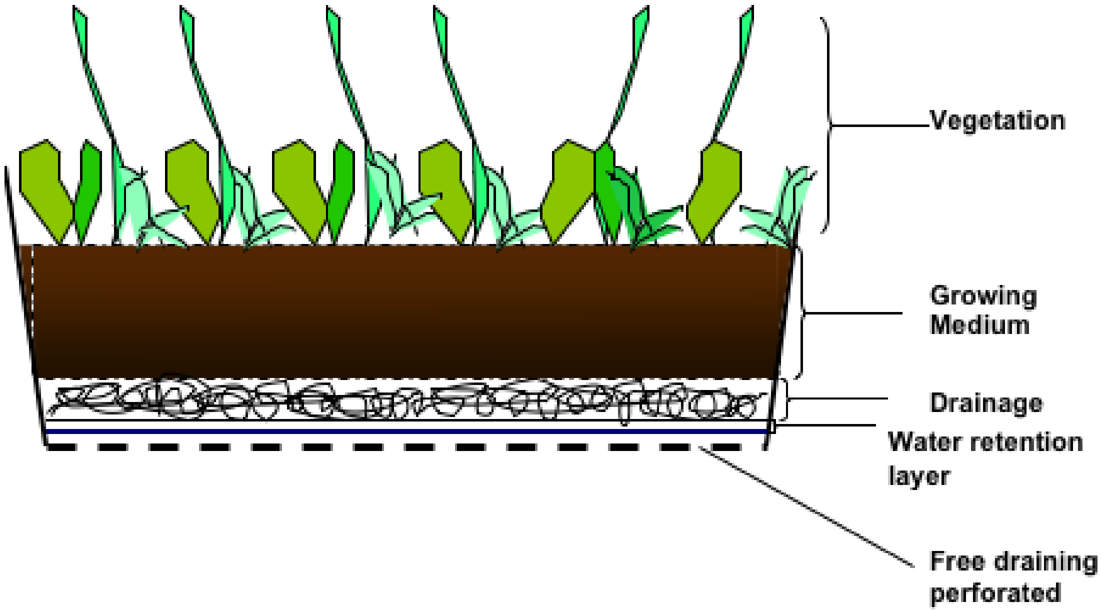


Figure 2. Typical module design in green roof studies. Holes exist in the bottom of the module with a drainage mat placed inside. Growth media is then placed on top with vegetation planted inside (E.P.I.C Lundholm Lab: Ecology of Plants in Communities (©J. Lundholm; author gives permission to use this image, Aug. 30, 2021).

Figure 3. Example of square module with drainage mat barrier included. One module represents one replicate of a particular treatment.

A total of 180 modules were used in this experiment (16 treatment combinations with 10 replicates and 20 control modules) and nine cm of growth media was added to each module. Planted in each module containing growth media were nine native plant species (Table 1, Figure 4) previously discovered to perform well on green roofs at Saint Mary's University

(Macivor and Lundholm, 2011) (excluding the control treatments which contained growth media only). Depending on the desired combination; moss/lichen, *Sedum*, plugs direct seeding, local growth medium and commercial growth medium were added accordingly (Figure 9a, b, section 3.2).

Table 1. Native, *Sedum*, moss and lichen species used in this project. All species used have been previously tested and had successful growth and survival rates on green roofs in the Maritimes (MacIvor and Lundholm, 2011).

Type	Species Name	Common Name	Growth Form	Ecosystem Services Provided	Harvest Period/Collection
Native Species	*Solidago bicolor*	Silverrod	perennial herb	pollinator resources, enhances stormwater retention[1], visual appeal	August - October
	Symphyotrichum novi-belgii	New York Aster	perennial herb	pollinator resources, enhances stormwater retention, visual appeal	November
	Luzula Multiflora	Common Wood Rush	perennial herb	visual appeal	August - October
	Oenothera biennis	Evening Primrose	biennial herb	Pollinator resources[2], visual appeal	August - October
	Danthonia spicata	Oatgrass	perennial bunchgrass	low water requirements[1]	July - August
	Festuca rubra	Red Fescue	perennial sod grass	enhances stormwater retention [3]	August
	Rhodiola rosea	Roseroot	perennial succulent	pollinator resources, visual appeal, microclimatic cooling[1]	July - August
	Plantago maritima	Seaside plantain	perennial herb	carbon storage[20]	September
	Sibbaldiopsis tridentata	Three-toothed cinquefoil	creeping shrub	pollinator resources, visual appeal	August
***Sedum* Species**	*Sedum acre*	Goldmoss stonecrop	perennial herb	microclimatic cooling[4]	August - September
	Sedum album	White stonecrop	perenial herb	canopy density, microclimatic cooling[5]	September
	Sedum sexangular	Tasteless stonecrop	perenial succulent	microclimatic cooling[6]	August - September
Moss Species	*Racomitrium lanuginosum*	Woolly moss	Moss	Weed reduction, lower substrate temperature[7]	March
Lichen Species	*Cladonia* spp.	Reindeer Lichen	Lichen	Weed reduction[8], lower substrate temperature[7]	March

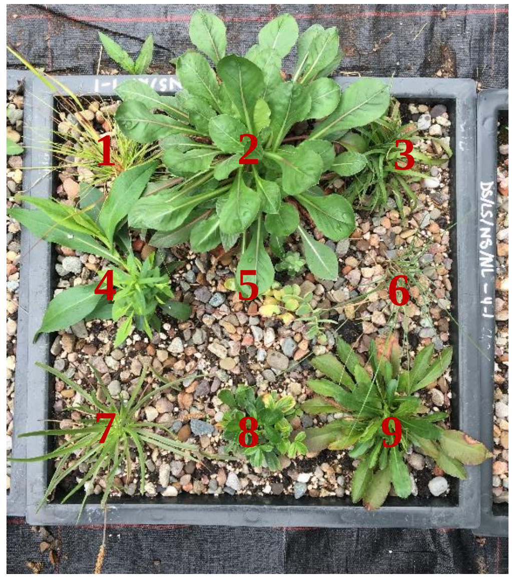


Figure 4. Arrangement of the nine native species used in each module of the study. Species were arranged in a 3 x 3 grid and randomly arranged in each module.

<u>*3.2 Treatment Combinations*</u>

Four experimental factors were evaluated throughout this experiment. These include 1) an establishment method of direct seeding vs. plug planting; 2) comparison of two substrates: locally made growth medium vs. industry green roof growth medium; 3) inclusion of *Sedum* species vs. no *Sedum* species; and lastly 4) inclusion of lichen/moss vs. no lichen and moss. This resulted in a total of 16 combinations of treatments (codes found in table 5). The terms growth media, substrate and soil have been used interchangeably throughout this study when referring to media that the plants grew in.

1) The first treatment, direct seeding vs. plug planting tested the difference in time and monetary costs while also measuring the effectiveness of the establishment method. Prior to the 2020 growth season in September 2019, seeds were collected in a local coastal barren (ecosystem characterized by harsh climatic conditions and by shrub

dominated plant communities (Porter et al., 2020)). Plugs were planted ahead of time using the stored seeds of each native species starting November 1st, 2019 in a green house. Plants were planted in 63.5 cm x 25.4 cm trays with seeds sprinkled over the Promix HP Mycorrhizae High Porosity substrate (Figure 5). Trays were then placed under full spectrum fluorescent grow lights (18 hrs. days) until seedlings grew. Once seedlings were present, they were moved into thirty-two 7.6 cm x 7.6 cm starter pots with three seedlings per pot (resulting in 96 total plants). Once species began to grow, they were transplanted into bigger 15.24 cm x 15.24 cm pots with one plant per pot and moved into a green house. In the green house, treatments were watered with tap water twice weekly until planted in their appropriate modules outside which took place June 15, 2020 to June 19, 2020. Plugs were planted into modules in a random 3 x 3 grid pattern (Figure 4) resulting in nine native plant species per module. The plug treatment took up 80 modules.

Direct seeding treatments received the native plant seeds outside starting on June 22, 2020 to June 26 2020. Seeds were distributed in the same random grid pattern as the plugs and included 10 seeds per section. Growth media was lightly sprinkled over the seeds by hand.

After all treatments were planted, modules were watered twice weekly with tap water for the first two weeks (until July 3rd for plugs and July 10th for seeds) to ensure establishment. After this, modules did not receive any additional water and relied on natural rain events except for one supplemental watering on August 10th as the prior week was extremely dry. Plants were noticeably drying; thus, water was provided to prevent further death.

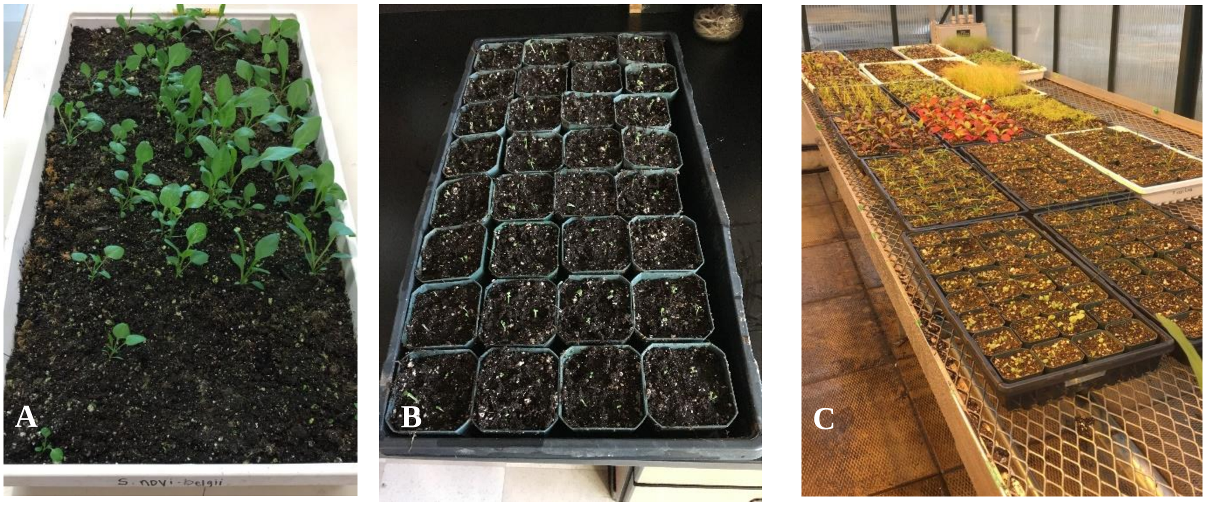


Figure 5. Examples of plug planting set-up at the beginning of the study. The plants began in their own 63.5 cm x 25.4 cm in tray (A), then were separated into smaller starter pots (B). The plants were then transferred from grow lights into a greenhouse setting (C).

2) The second treatment, comparison of locally sourced vs. commercial green roof growth media tested the possibility of using locally sourced materials that are environmentally friendly and cost effective. The commercial growth medium used was (Sopraflor X™) purchased from SOPREMA Inc. in Quebec. The composition of locally made growth medium was formulated based on the Sopraflor X™ mixture (Table 3) which follow the FLL guidelines. Materials used included small pea stone (1/4" to 1/2") (©Shaw Resources, Dartmouth, N.S), fine sand (©Shaw Resources, Dartmouth, N.S), compost (Halifax Ragged Lake Compost Facility, Halifax, Nova Scotia) and Pro-Mix Perlite™ (Kent, Halifax, Nova Scotia).

   The locally sourced soil was constructed based on the commercial soil make up (Table 3, Table 2). Measurements were taken based on ratios and were measured by volume. For media mixing and application, ten modules were used to make one batch of local soil. Pea stone was measured into 5.5 modules, perlite was measured into 1.5 modules, compost was measured into one module and sand was measured into two modules (5.5:1.5:1:2). All modules were then slowly added into one large mixing container and mixed thoroughly with a shovel and hand trowel. The growth media was then distributed into ten modules up to the nine-inch mark. This process was repeated seven more times to make up the 80 modules for the local soil treatment.

Table 2. Composition of locally made growth medium based on mineral and organic matter percentages from the Sopraflor X™ commercial media.

Materials	Percentage of Composition	Parts (1 module = 1 part)
Pea Stone	55%	5.5
Perlite	15%	1.5
Sand	20%	2
Compost	10%	1

Table 3. Properties of Sopraflor X™ extensive green roof media provided by SOPREMA Inc.

Properties	Sopraflor X
Vegetation	*Sedum*s, dry prairie grasses, dry flower meadows, and vegetation with low water needs
Composition	Mineral aggregates, professional peat, sand, and compost from vegetable matter
Volumetric water retention	30 - 40 %
Air-filled porosity	20 - 30 %
Total porosity	60 - 70 %
Bulk density, dry	675 - 1100 km/m3
Bulk density, initial	950 - 1050 kg/m3
Bulk density, saturation at field capacity	1150 - 1250 kg/m3
Organic matter, dry base	5 - 10 %
pH	6.0 -7.0
Mineral aggregates (Volume)	70%

3) The third treatment included the addition or absence of *Sedum* species mixed in with the native plant species used in this study. In treatments that included *Sedum* species, three different species were used and included *Sedum acre*, *Sedum sexangulare* and *Sedum album*. *Sedum* were taken from existing plants located on the atrium green roof at Saint Mary's University. A sharp-edged trowel was used to take a small *Sedum* clipping with five to six stems including their roots (Figure 6). One of each clipping was then transplanted into the appropriate treatments and modules (Figure 9a,b) in between the native plant species (Figure 7). *Sedum* were transplanted at the same time as native plants.

Figure 6. Example clipping of *S. sexangular* used in *Sedum* treatments in this study. Clippings were taken with a sharp-edged trowel and transplanted into appropriate modules.

Figure 7. Example of *Sedum* formation when included with native plant mixture. Each module including *Sedum* were randomly placed in between the native plants.

4) The last treatment used in this study was the addition or absence of moss and lichen species in the native plant mixtures. The moss species used was *Racomitrium lanuginosum* and the lichen species used was *Cladonia* spp (*Cladonia portentosa)*. The moss and lichen were collected from coastal barrens near Halifax, Nova Scotia by picking the species directly from the ground and placing them into plastic bags to dry. Collection took place in November 2019 and was stored at room temperature after cleaning off excess dirt. Approximately, 200 mL of each species was added into the modules by crushing and sprinkling over the top of the growth medium. Tap water was then sprayed over top of the moss and lichen. Moss and lichen addition should have been achieved in March 2020, but due to the COVID-19 pandemic, closure of the university occurred and their additions did not occur until July 2020. Unfortunately, this delay proved detrimental to the establishment and growth of the

moss and lichen portion of this project and had no significance on the treatment combinations of this study. Therefore, this treatment was omitted from data analysis.

Treatments contained 10 replicates each (Figure 9 a,b). Four of the replicates were placed at block 1, three replicates were placed at block 2 and three replicates were placed at block 3. Four control modules of each growth media were placed at block 1, three were placed at block 2 and three were placed at block 3. Native plants were arranged in a random grid pattern and modules were randomly placed throughout the block. Block 1 had modules aligned in two rows, then one walking path to allow passage (30 cm) (Figure 9b). Three rows were located in the middle of the block with one more walking path on the other side. Then the last section of the block contained two more rows. Blocks 2 and 3 had one walking path with two rows of modules on either side. Modules were randomly placed throughout the block.

While this was the initial setup, because the moss and lichen treatments were considered not significant, they were removed from analysis. Therefore, instead of 16 different treatment combinations, the combinations were reduced to eight, resulting in each combination having 20 replicates. Thus, block 1 contained eight replicates, block 2 contained six replicates and block 3 contained six replicates.

3.3 Measured Variables

In order to determine the effectiveness and most desirable treatment combination, multiple variables were measured and recorded which include: recording monetary and time costs, canopy density, floral coverage, plant heights, stormwater retention, growth media temperature, and nutrient concentration analysis.

3.3.1 Canopy density

Canopy densities (including weeds/spontaneous growth) were recorded once a month by using the point intercept method (Floyd and Anderson, 1987) with a metal pin frame (Figure 8). The frame measured 30 cm high with a length of 36 cm and a width of 36 cm. The frame also had 16 equally spaced rods which were 6 mm in diameter and rested on the edge of the module. Pins were located approximately 2 cm above the growth medium. Once the pin frame was properly in place, the number of contacts on the rods from a particular plant species was recorded. Should a species be present in a module, but made no contact with a rod, the pin contact was recorded as one. If a species was observed to be dead that month, then the pin contact was recorded as zero. The sum of all contacts for a species and then the sum of all contacts in a treatment combination was termed “canopy density”. This method of measuring canopy density is essential when characterizing ecosystems and measuring productivity and uses a non-destructive estimation approach (Jonasson, 1988).

Figure 8. Metal pin frame used for canopy density analysis. The frame contained 16 equally spaced rods which were 6 mm in diameter and rested on the edge of the module. Pins were located approximately 2 cm above the growth medium.

3.3.2 Floral Coverage

Floral coverage was recorded for each module every two weeks starting in July 2020 and ending in September 2020. Only flowers that were completely opened and not dead were recorded as they could be accessed by pollinators. Grass flowers were not considered in these estimates as they are not insect pollinated. Floral coverage was estimated using a modified version of the digital grid overlay method, where instead of analyzing digital pictures, a grid was used in the field at the time of data collection. Floral cover was recorded using a 55 x 55 square sheet of grid paper. Each square represented 0.033% of the module's surface area which was calculated by:

$$\textbf{\textit{One square on grid}} = \frac{\mathbf{1}}{(\mathbf{55} * \mathbf{55})} \times \mathbf{100} = \mathbf{0.033}\ \%$$

Each flowering species was then placed onto the grid paper to approximate floral cover percentage (Table 4). This included both flowering native and *Sedum* species and was done with multiple flowers of the same species to get a more accurate average floral coverage percentage. Flowers (capitula for *Solidago* and *Symphyotrichum*) were then counted in each module and multiplied by their average floral coverage percentage to get the floral coverage for each module:

$$\textbf{\# of flowers per species (x)} * \textbf{Average floral cover \% for species (x)} \\ = \textbf{Total floral cover \% for species (x)}$$

In order to get the total flower coverage per module, floral cover percentage was added together for each species in a module.

Table 4. Flowering species used in this study with their average floral cover percentage. Values indicated were multiplied by flowers present in a module.

Species	Percentage (%)
S. bicolor	0.033
S. novii-belgii	0.528
O. biennis	0.264
P. maritima	0.033
S. acre	0.033
S. sexangulare	0.033
S. album	0.033

3.3.3 Heights

As with floral coverage, heights of plants were also recorded every two weeks starting in July 2020 and ending in September 2020. Collection dates took place on July 28, August 10, August 27, September 9 and September 24. Only native plants were measured (excluding *Sedum* heights from analysis) and only living vegetation was recorded. Heights were measured with a meter stick and held at the base of the plant touching the top of the soil. Measurements were in centimeters to the nearest tenth.

3.3.4 Stormwater Retention

As an indicator of green roof benefits, stormwater retention was measured throughout the duration of the summer (1x/month). Water retention was only collected on days with sunshine and no rain. Initially, all modules were weighed on an electronic weigh scale to the nearest thousandth of a kilogram. Once the air-dried modules were weighed, 2 L of tap water was measured and placed into a watering can to distribute over each module over a 30 second period. The 2 L amount of water was used to simulate a rain event of 5 mm. This was calculated by:

$$\textbf{Surface area of module with soil } (\mathbf{3888\ cm^2}) \times \mathbf{0.5\ cm\ of\ rain} \cong \mathbf{2000\ cm^3} = \mathbf{2}\ \boldsymbol{L\ of\ water}$$

Ten minutes after the water was added to the module any water remaining water was considered the water retained, and the module was weighed a second time. The amount of water retained by each module was calculated by:

$$\boldsymbol{Second\ module\ weight\ after\ water\ addition}\ (\boldsymbol{kg}) - \textbf{First module weight before water addition } (\mathbf{kg}) = \textbf{Water retained in growth media } (\mathbf{kg})$$

One supplemental irrigation was supplied to all modules on August 10th to prevent total plant loss from an extreme drought.

3.3.5 Growth Media Temperature

Growth media temperature from the bottom of each module were collected and recorded using a Taylor 9878 Slim-Line Pocket Thermometer probe (Commercial Solutions Inc., Edmonton, AB, Canada). Collection dates occurred on July 21, 2020, August 17, 2020 and September 28, 2020. Readings were taken from the center of each module on days without overcast or rain and at solar noon (~ 12:00 p.m. to 1:30 p.m. AST). The probe was inserted into the growth medium at the base of the module (~ 7-9 cm).

3.3.6 Nutrient Analysis of Growth Media and Runoff

A small sample of media and water runoff were collected from control modules at the beginning of the experiment in July 2020 and a nutrient analysis were conducted for both growth media types in this study. The samples were taken from control modules with no vegetation growth and included five samples from each media for the water runoff and three samples each for the soil analysis. Samples were used from all study blocks. For water runoff samples, 250 mL was collected at the same time as the water retention analysis by placing a plastic container under the module to collect the water during the 10-minute draining period. Samples were then stored in a freezer until January 2021 where they were then sent away for testing. Analyses included Nitrogen percentage, pH, potassium, phosphorus and various other nutrients and minerals (Table 12, 13) and was conducted by The Department of Agriculture, Laboratory Services in Truro, Nova Scotia. Accredited methods used by the Department of Agriculture include:

3.3.5.1 Growth media tests:

- LSAL408 Determination of Mehlich III Extractable Major and Trace Metal Ions in Soil by ICP-OES.
- LSAL409 Determination of Soil Water pH and Lime Requirement using Adams-Evans Buffer by AS3010D pH Analyzer.

3.3.5.2 Runoff tests:

- LSAL400: Major Ions and Trace Metals by ICP-OES (Modified SMEWW 3120B and 2340B).
- LSAL403: Conductivity of Water by Conductivity Meter (Modified SMEWW 2510B).
- LSAL406: Determination of Nitrate + Nitrite, Chloride and Alkalinity in Drinking and Environmental Water by Flow Injection Analysis.
- LSDL681: Coliform and E. coli Determination in Water Using Colilert and Colisure (Modified SMEWW 9223).

3.4 Statistical Analysis

All statistical analysis for this project were conducted using the software program R and R studio (1.1.436) (R Core Team, 2018). All data were tested for normality prior to analysis using a combination of Shapiro-Wilks's normality test and comparisons of residuals. If data were not normally distributed ($p < 0.05$), then a Tukey Ladder of Power transformation was used. This transformation finds the power transformation that made the data fit the normal distribution as closely as possible.

This study used a mixed model Analysis of Variance (ANOVA) to determine significant effects and interactions between treatments. Firstly, mixed models were run for each of the following variables: canopy density, height, flower cover, water retained, and temperature as the response variable; block was a random effect; fixed effects were the fully crossed soil type × *Sedum* presence/absence × propagation type factors. Canopy density was included as a continuous variable in ecosystem service analysis (water retention and temperature) as this often had an effect on the response variable. In order to determine if block should be included in the model as a random effect, the model was compared to another model fitted with just the fixed effects and excluding the random effects. If the model including the random effect of block was a better fit, it was used as the main model for that response variable. If the ANOVA produced a significant interaction or effect ($p < 0.05$), then a Tukey Pairwise Comparison test was conducted to determine which treatment combinations differed significantly from one another.

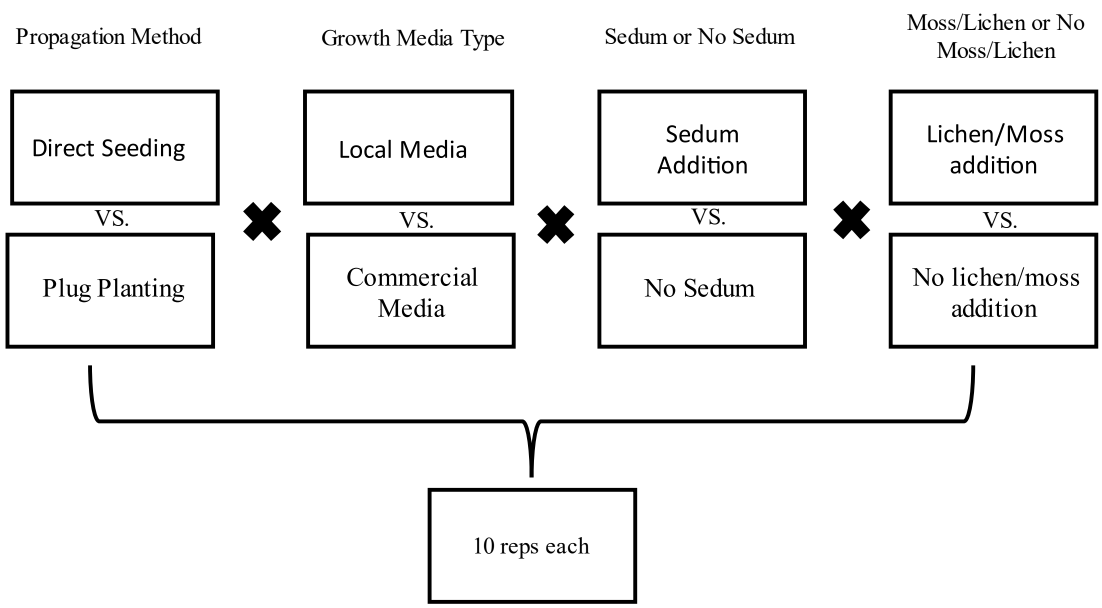


Figure 9a. Schematic representation of the fully crossed treatment combination used in this study. Each treatment group has two variations and when crossed, produce 16 possible treatment combinations. Each combination includes 10 replicates for a total of 160 modules. Each module also contained a random arrangement of the nine native plant species used in this study.

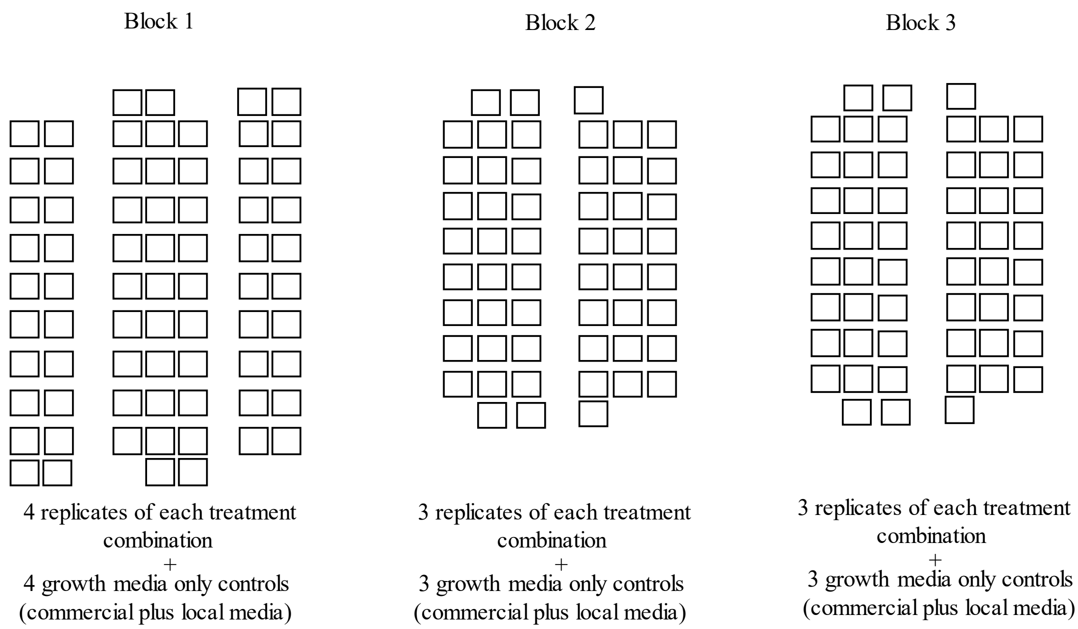


Figure 9b. Depiction of project set up at each different block site. Four replicates of the treatment combinations were allocated to block 1 and had four growth media only controls of each growth media for a total of eight controls. Block 2 and 3 had three replicates of each treatment combination and had three controls of each growth media type. Modules were randomly arranged and included walkways to allow for movement between the blocks.

Table 5. Codes used for the treatment combinations and species.

16 Treatment Combinations	**9 Species**
DS: Direct Seeding	**SB:** *Solidago bicolour*
PP: Plug Planting	**SNB:** *Symphyotrichum novi-belgii*
LS: Local growth medium	**LM:** *Luzula multiflora*
CS: Commercial growth medium	**OB:** *Oenothera biennis*
S: *Sedum*	**DS:** *Danthonia spicata*
NS: No *Sedum*	**RR:** *Rhodiola rosea*
L: Lichen/Moss	**PM:** *Plantago maritima*
NL: No Lichen/Moss	**ST:** *Sibbaldiopsis tridentata*
	FR: *Festuca rubra*

Chapter 4: Results

4.1 Summary of Results

Plant growth

Overall, the treatment with the most canopy density and tallest plant heights in July was plug method, local growth media, added *Sedum* (PP/LS/S) and plug method, local growth media, and no *Sedum* (PP/LS/NS). Results were similar in August and September as the highest canopy density and tallest plants were in the plug method in local media with *Sedum* (PP/LS/S) treatment (Figure 10, A - C, Figure 13, A - C) and plug method in local media with no *Sedum* (PP/LS/NS), respectively. Notable interactions were observed between treatment combinations and should be taken into consideration. Both canopy density and heights interacted with soil/propagation. Heights also had a two-way interaction between *Sedum*/propagation. Canopy density had two three-way interactions between soil/propagation/*Sedum*.

Ecosystem Services

In July and August, the treatment with the highest flower cover was the plug method with commercial soil and *Sedum* included (PP/CS/S). In September, the treatment with the highest percentage of flower cover was the plug method in local soil with no *Sedum* (Figure 14, A-E). Treatments containing plugs, commercial soil and *Sedum* provided the best results for water retained and growth media temperature (Figure 15, Figure 16). Interactions occurred between propagation/soil for both services. Both plug and direct seeding treatments did best in commercial soil for retention and had similar results indicating that the soil may have been mostly responsible for the water retention. However, to maximize the amount of water retained, plugs should be used. Similarly, the commercial media also had the lowest temperatures and when combined with a higher canopy density, had even lower temperatures.

Practical Considerations

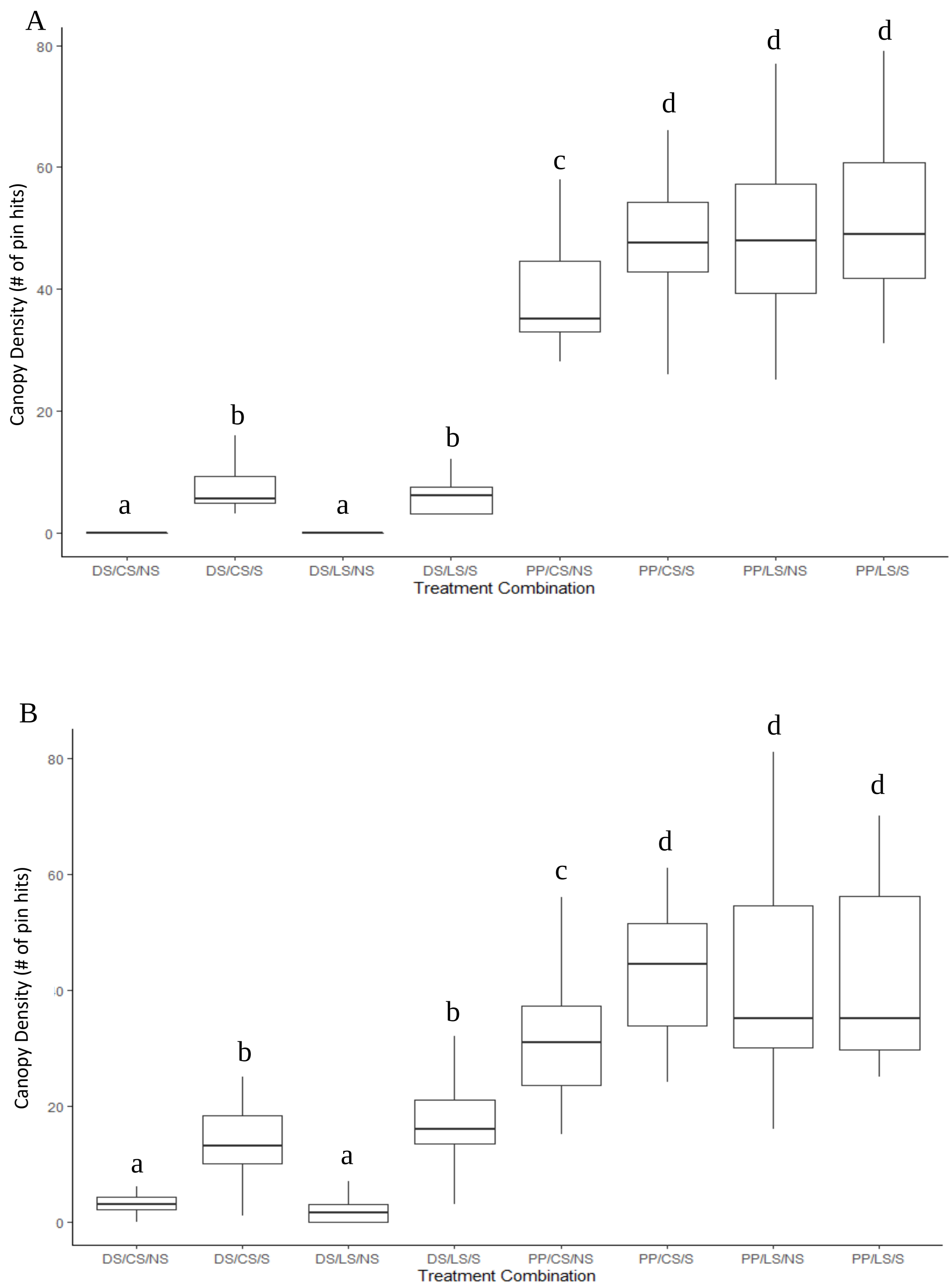
The direct seeding method took significantly less time and was cheaper than the plug planting method (Table 16). However, the plug planting method had greater canopy density results and limited the number of weeds present in plug modules. Soil composition was also responsible variation in nutrient concentration levels and weed canopy density, such that commercial growth media presented highest in each. Block also had an impact on the success of plants. Block 1 had the lowest temperatures and most successful plant growth. Block 2 and 3 had higher temperatures with the highest observed at block 2. The least successful plant growth occurred at block 2 (Figure 12, Figure 17).

4.2 Canopy density

Propagation type, *Sedum* addition and soil type all had significant effects on canopy density. Each month was analyzed separately and different patterns emerged in each month. In July, one significant interaction took place between the propagation and soil treatment ($p = 0.0083$) (Table 6, A). Plug planting propagation resulted in a much higher canopy density overall. There was a larger number of biomass pin hits in the plug treatment when local soil was used rather than the commercial soil (Figure 10, A-C). Direct seeding treatments did not do better or worse in either of the soils. Overall, the treatment that yielded the most biomass was the treatment "PP/LS/S" and "PP/LS/NS" with a mean canopy density of 51.4 (± 3.08) and 49.2 (± 3.11) respectively. DS/CS/NS, DS/LS/NS and both control treatments all had zero biomass for the month of July. Block had a significant effect on the biomass in July ($p < 0.0017$) (Figure 10, A). The block with the highest canopy density was block 1 at a mean of 28.0 (± 6.19) and block 2 had the least amount of canopy density with a mean of 21.1 (± 4.34) (Figure 12, A)

In August, a three-way interaction took place between *Sedum* occurrence, propagation and soil type, ($p < 0.0010$) (Table 6, B). Both plug propagation and direct seeding had the highest biomass when containing *Sedum* in the local soil. Directly seeded modules with no *Sedum* had higher biomass in the commercial soil. In plug modules without *Sedum*, biomass was higher in the local soil. Overall, the treatment with the most canopy density was PP/LS/NS with a mean of 43.4 (± 4.10) (Figure 10, B). The treatment with the lowest canopy density was DS/LS/NS with a mean of 2.1 (± 0.512). Block had a significant effect on the biomass in August ($p < 0.0001$) (Figure 12, B). The block with the most canopy density was block 1 with a mean of 30.8 (± 5.48) and the block with the least amount of canopy density was block 3 with a mean of 18.8 (± 2.53). Block 3 had the most exposure to wind and direct sunlight and block 1 had the least exposure (Figure 12, B)

A three-way interaction also occurred in September between propagation, soil and *Sedum* ($p = 0.0361$) (Table 6, C). The combination with the highest canopy density was the plug treatment containing local soil and no *Sedum* (Figure 10, C). However, plugs in the treatments with *Sedum* in commercial soil did comparably well. Direct seeding treatments did best in local soil with *Sedum* included, but did best in commercial soil when *Sedum* was not included. The treatment with the highest canopy density was PP/CS/S with a mean of 45.0 (± 2.95). The treatment with the lowest canopy density was DS/LS/NS with a mean of 5.5 (± 1.06). Block had a significant effect on biomass in September ($p < 0.0021$) (Figure 12, C). Block 1 was observed to have the highest canopy density with a mean of 35.5 (± 5.52) and block 3 had the least amount of canopy density with a mean of 25.0 (± 3.62) (Figure 12, C)


A
Canopy Density (# of pin hits)
80
60
40
20
0
a
b
a
b
c
d
d
d
DS/CS/NS
DS/CS/S
DS/LS/NS
DS/LS/S
PP/CS/NS
PP/CS/S
PP/LS/NS
PP/LS/S
Treatment Combination
B
Canopy Density (# of pin hits)
80
60
20
0
a
b
a
b
c
d
d
d
DS/CS/NS
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PP/LS/NS
PP/LS/S
Treatment Combination

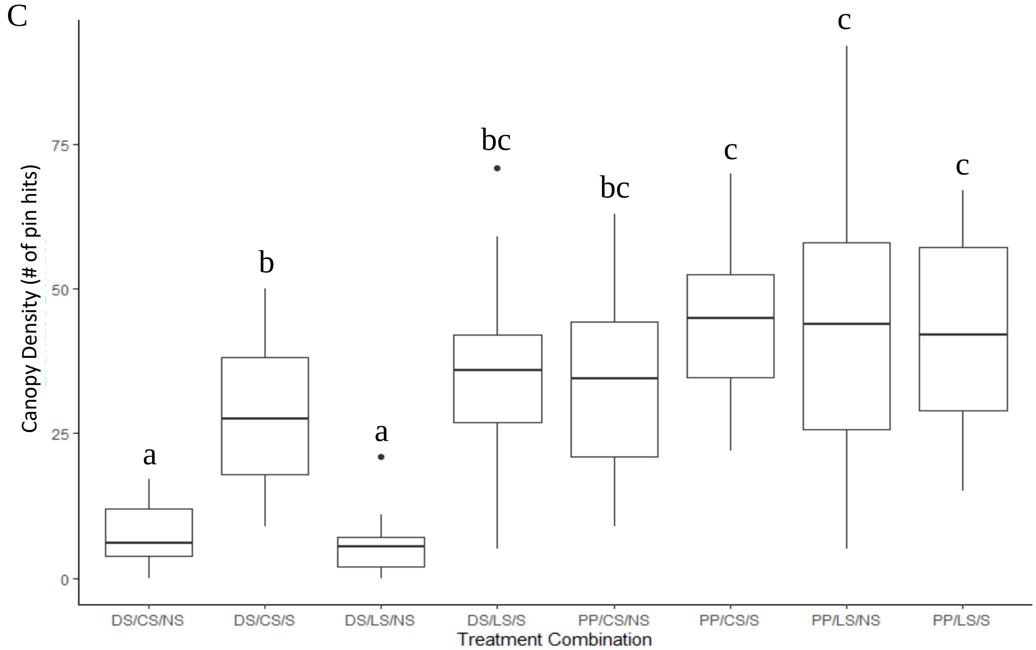


Figure 10. Box plots of canopy density measured comparing the different treatment types using the pin frame method on July 20, 2020 (**A**), August 17, 2020 (**B**) and September 24, 2020 (**C**). Boxes without shared letters are significantly different.

Canopy density was collected for weeds throughout the duration of the study to determine which treatments did best at limiting spontaneous growth (Figure 11). There was no significant effect from block and thus block was excluded from the model. No spontaneous growth was observed in July as modules were still in their establishment period and did not have time. In August, a significant interaction between soil and propagation was noted ($p < 0.0041$) (Table 7, A). The direction of this interaction indicates that the direct seeding method had more weeds than the plug planting method, and also was colonized by more weeds when in the commercial soil. The plug planting modules had almost no weeds when either soil type was used. In September, (Table 7, B) plug planting modules had fewer weeds than the direct seeding method.

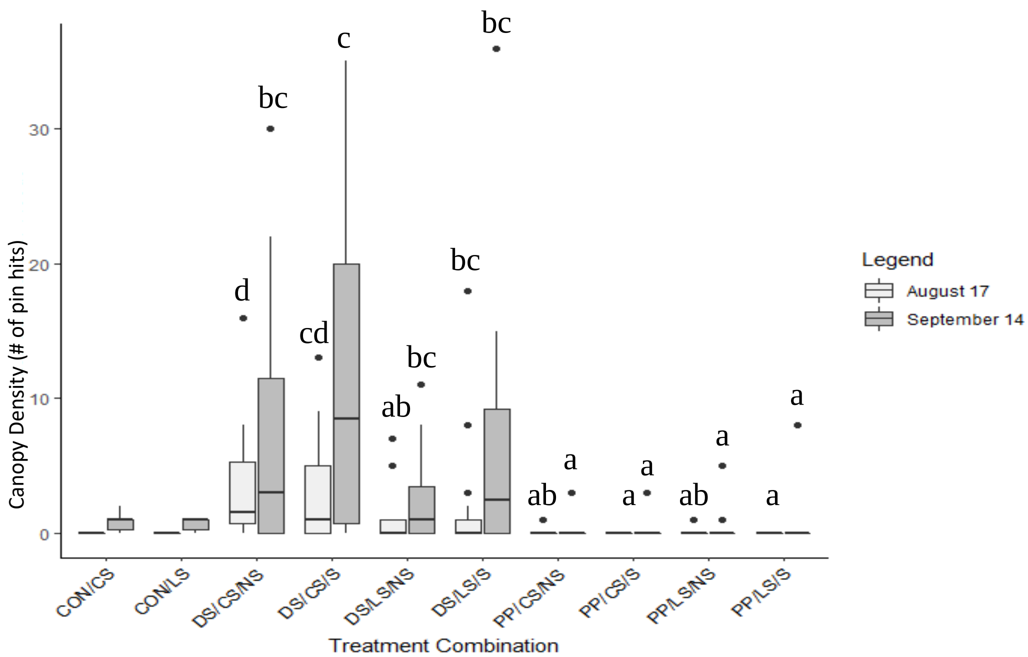


Figure 11. Box plots of canopy density for weeds (spontaneous plant growth) on August 17, 2020 and September 24, 2020. July did not have weeds for any of the treatments. Boxes without shared letters are significantly different.

Table 6: ANOVA tables for each month of canopy density including p-values for significance.

A) July: Canopy density	Trans	DF	F-value	P-value
July 2020	None			
Propagation		1	2100.7454	<.0001
Soil		1	4.2966	0.0178
Sedum		1	73.2982	0.0001
Propagation:Soil		1	6.5637	0.0083
Propagation:*Sedum*		1	16.5618	0.7819
Soil:*Sedum*		1	2.8382	0.1107
Propagation:Soil:*Sedum*		1	1.4294	0.1864

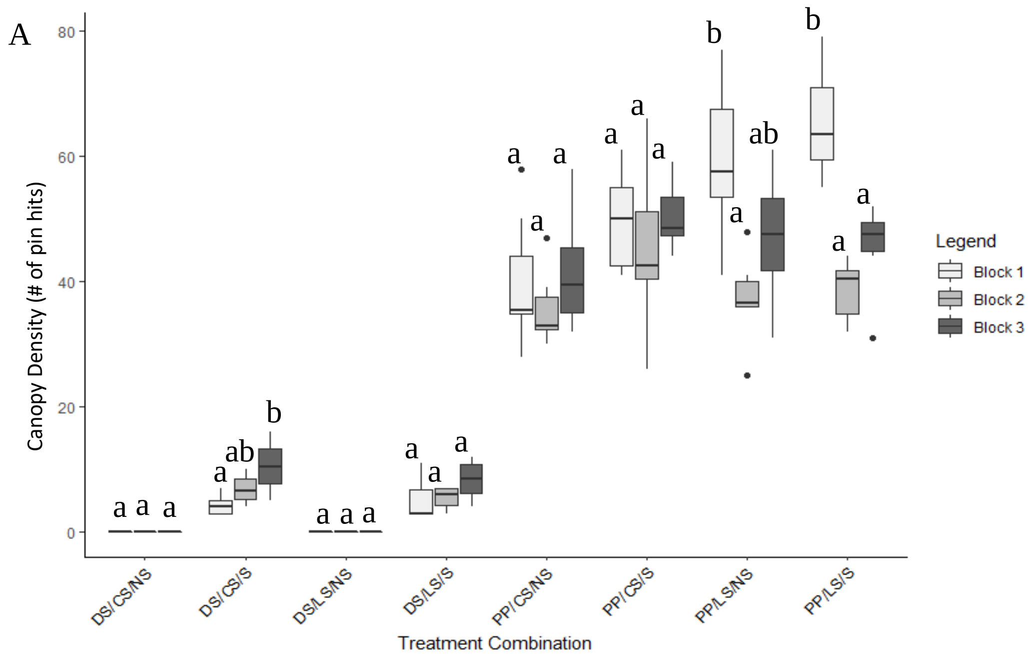
B) August: Canopy density	Trans	DF	F-value	P-value
Treatment	Tukey			
Propagation		1	678.9846	<.0001
Soil		1	3.2498	0.0734
Sedum		1	91.5032	<.0001
Propagation:Soil		1	2.7329	0.1004
Propagation:*Sedum*		1	41.9936	<.0001
Soil:*Sedum*		1	0.6283	0.4292
Propagation:Soil:*Sedum*		1	11.2863	0.0010

C) September: Canopy density	Trans	DF	F-value	P-value
Treatment	None			
Propagation		1	105.66276	<.0001
Soil		1	1.92444	0.1674
Sedum		1	48.74407	<.0001
Propagation:Soil		1	0.12425	0.7250
Propagation:*Sedum*		1	20.58405	<.0001
Soil:*Sedum*		1	0.03737	0.8470
Propagation:Soil:*Sedum*		1	4.47312	0.0361

Table 7: ANOVA tables for each month of weeds canopy density including p-values for significance.

A) August: Estimated weed canopy density	Trans	DF	F-value	P-value
Treatment	Tukey			
Sedum		1	0.3808	0.5381
Propagation		1	66.7159	<.0001
Soil		1	12.0906	0.0007
Sedum:Propagation		1	0.2614	0.6099
Sedum:Soil		1	1.1139	0.2929
Propagation:Soil		1	8.4856	0.0041
Sedum:Propagation:Soil		1	0.2413	0.6239

B) September: Estimated weed canopy density	Trans	DF	F-value	P-value
Treatment	Tukey			
Sedum		1	2.437	0.1205
Propagation		1	88.972	<.0001
Soil		1	2.556	0.1120
Sedum:Propagation		1	2.735	0.1003
Sedum:Soil		1	0.027	0.8690
Propagation:Soil		1	3.815	0.0526
Sedum:Propagation:Soil		1	0.066	0.7971



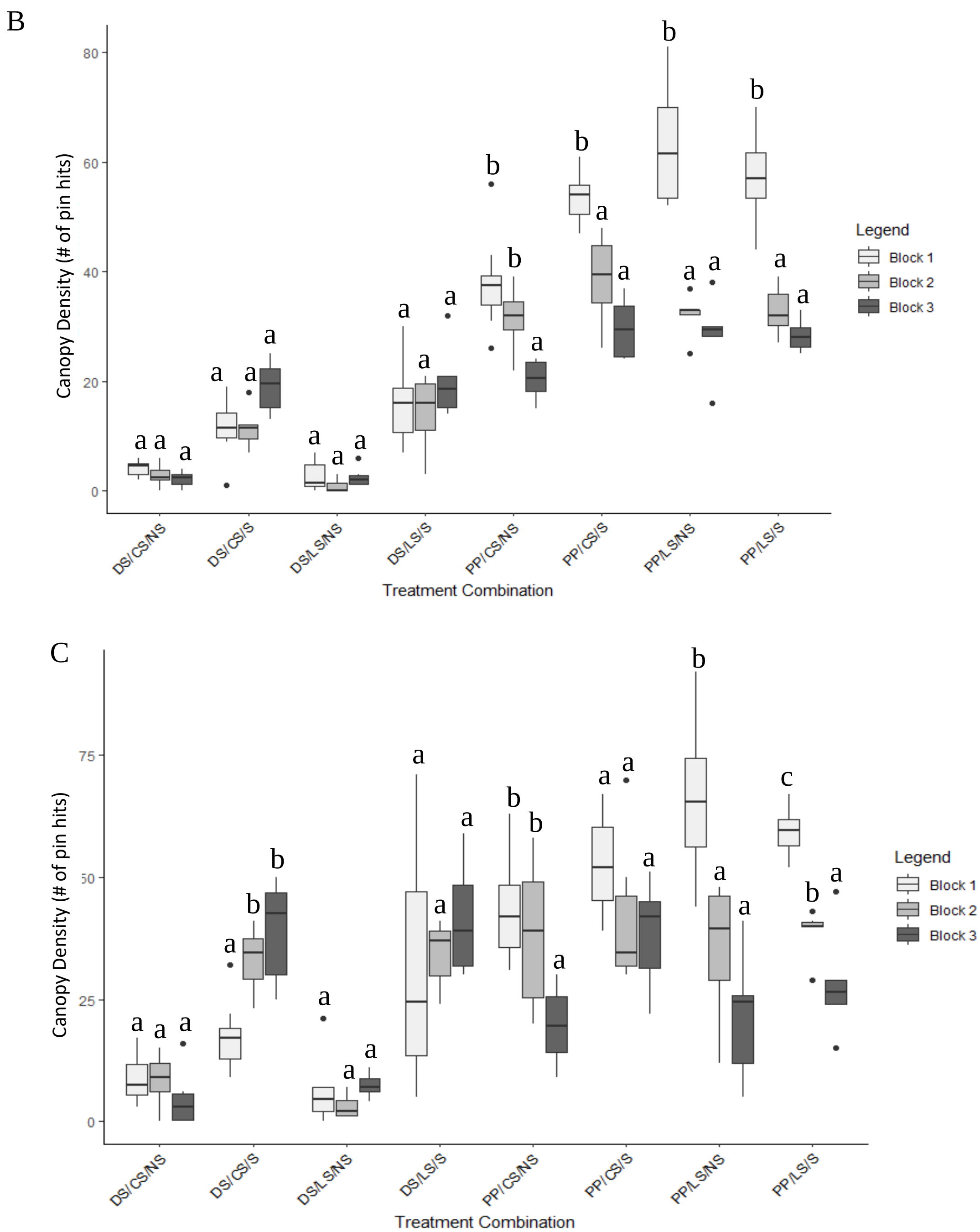


Figure 12. Block effect for the canopy density throughout the summer on July 20, 2020 (A), August 17, 2020 (B) and September 24, 2020 (C).

4.3 Plant Heights

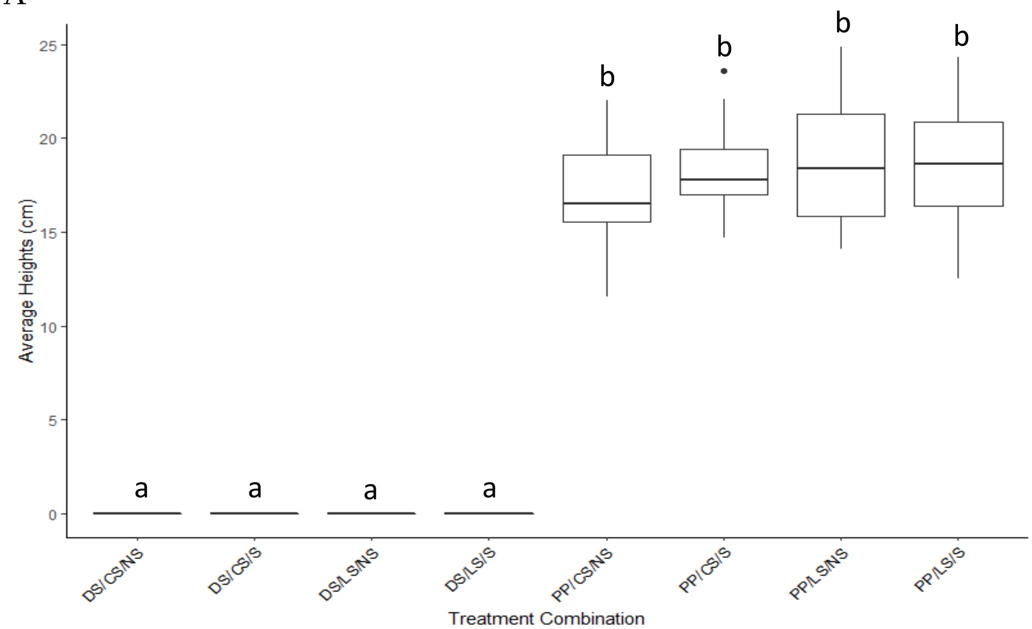
Plant heights were measured for each module roughly every two weeks throughout the summer of 2020. At the beginning of the experiment, on July 28, plug planting treatments had significantly larger heights compared to the direct seeding method (Figure 13, A). The treatment with the largest mean height was 'PP/LS/S' with 18.7 (± 0.731) cm. No growth was observed in the direct seeding treatments at this time.

On August 10, direct seeding treatments were measurably taller than at the start, but plug planting treatments were still the tallest on average (Figure 13, B). Two interactions occurred on August 10, including propagation/soil and propagation/*Sedum*. When direct seeding was used, plants were taller in the commercial soil. However, when plugs were used, plants were generally taller in the local soil. The interaction between propagation and *Sedum* showed that when direct seeding was combined with no *Sedum*, plants were taller. Alternatively, when plugs were combined with *Sedum*, plants were taller. The treatment combination with the tallest mean height was 'PP/LS/S/' at 21.7 (±1.46) and the treatment combination with the smallest mean height was 'DS/LS/S at 5.40 (± 1.08).

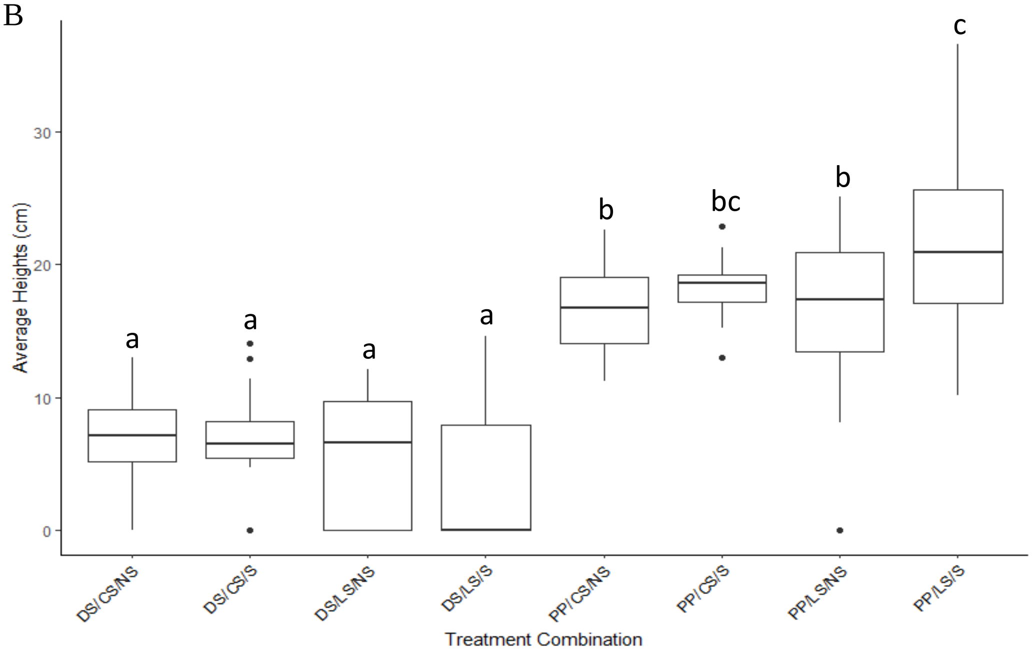
August 27 presented a similar result with an interaction occurring between propagation/soil (Table 8, C). Once again, propagation was found to have a significant effect on height where plug planting yielded taller plants than direct seeding. Direct seeding treatments did better when combined with commercial soil and plug planting treatments did better when combined with local soil (Figure 13, C). The treatment with the highest mean height was PP/LS/S at 20.2 (± 1.15) cm and the treatment with the lowest average height was DS/LS/S at 7.2 (± 1.64).

Height measurements of September (Sep. 9 and 24) had no interactions occur between treatments. There were however significant effects from propagation treatments (Table 8, D, E). On both dates, the plug planting treatments still had higher average heights than the direct seeding method. On September 9, the treatment with the tallest heights was PP/LS/S with a mean of 20.8 (± 1.46) cm and the lowest heights were observed in DS/CS/S with a mean of 9.56 (± 1.08) cm (Figure 13, D). On September 24 the treatment with the tallest heights was PP/LS/NS with a mean of 18.5 (± 1.10) cm. The treatment with the smallest heights was DS/CS/S with a mean of 8.82 (± 1.24) cm (Figure 13, E).

A

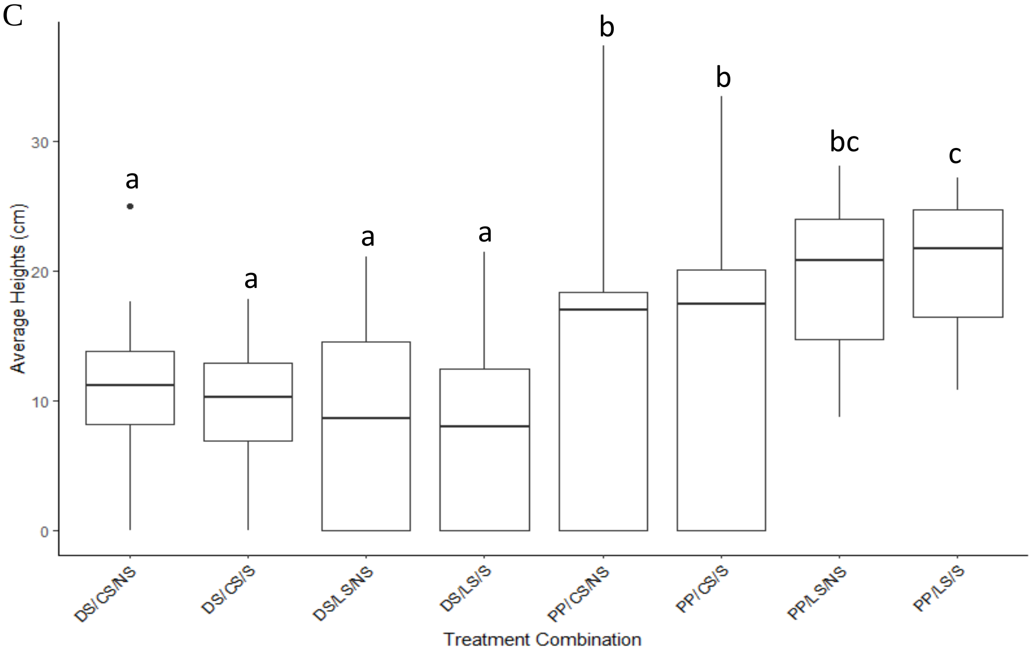


B



c
b
bc
b
a
a
a
a
30
20
10
0
Average Heights (cm)
DS/CS/NS
DS/CS/S
DS/LS/NS
DS/LS/S
PP/CS/NS
PP/CS/S
PP/LS/NS
PP/LS/S
Treatment Combination

C



b
b
bc
c
a
a
a
a
30
20
10
0
Average Heights (cm)
DS/CS/NS
DS/CS/S
DS/LS/NS
DS/LS/S
PP/CS/NS
PP/CS/S
PP/LS/NS
PP/LS/S
Treatment Combination

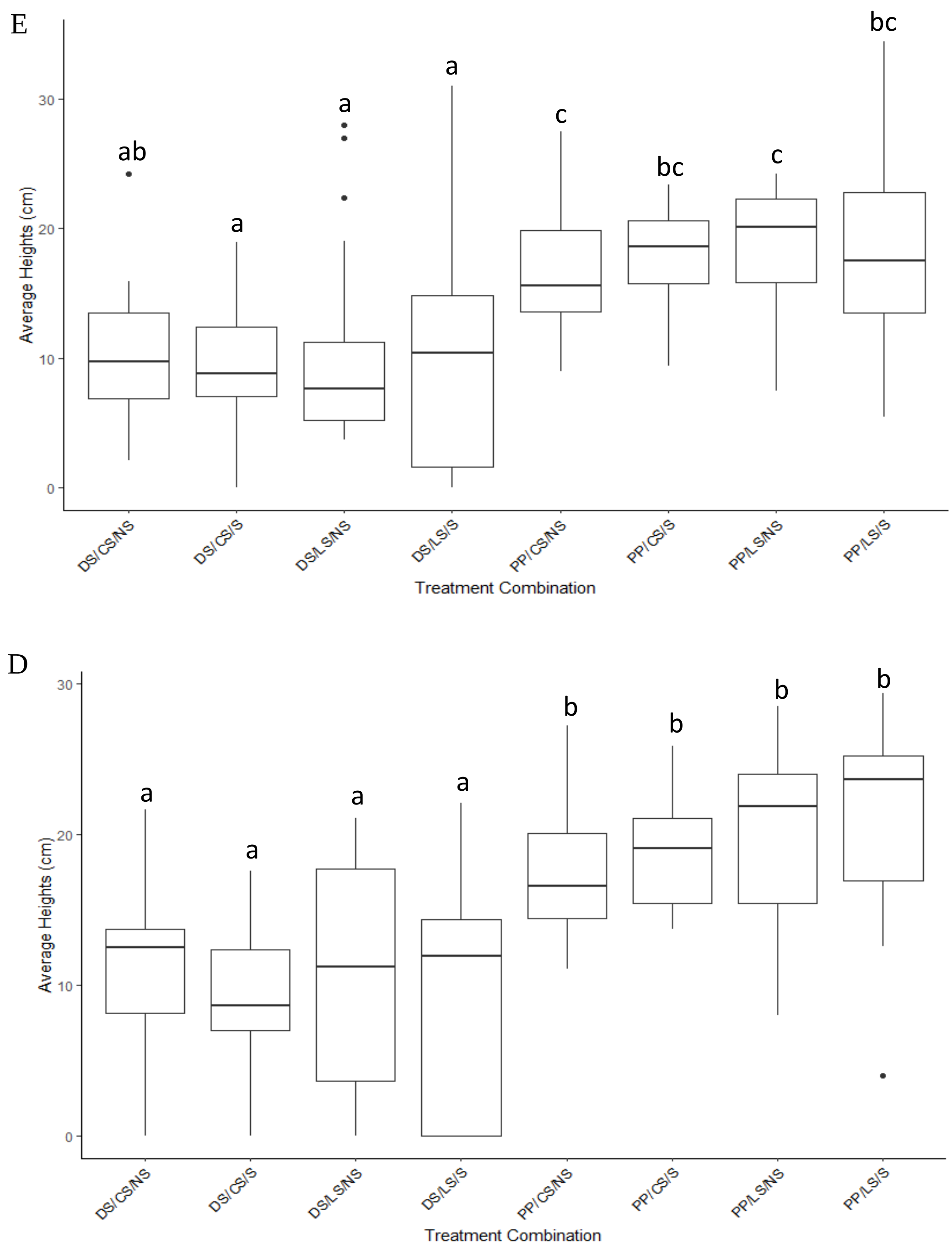


Figure 13. Average plant heights (cm) for each treatment module for the summer of 2020 including: July 28, 2020 (A), August 10, 2020 (B), August 27, 2020 (C), September 9, 2020 (D), and September 24, 2020 (E). Boxes without shared letters are significantly different.

Table 8. ANOVA tables for each date of average heights including p-values for significance.

A) July 28: Avg. Heights	Trans	DF	F-value	P-value
Treatment	None			
Sedum		1	0.8185	0.3671
Propagation		1	3055.8502	<.0001
Soil		1	2.6149	0.1079
Sedum:Propagation		1	0.8185	0.3671
Sedum:Soil		1	0.6923	0.4067
Propagation:Soil		1	2.6149	0.1079
Sedum:Propagation:Soil		1	0.6923	0.4067

B) August 10: Avg. Heights	Trans	DF	F-value	P-value
Treatment	None			
Sedum		1	3.05406	0.0826
Propagation		1	305.76398	<.0001
Soil		1	0.15330	0.6960
Sedum:Propagation		1	8.14482	0.0049
Sedum:Soil		1	0.76297	0.3838
Propagation:Soil		1	7.26709	0.0078
Sedum:Propagation:Soil		1	2.89329	0.0910

C) August 27: Avg. Heights	Trans	DF	F-value	P-value
Treatment	None			
Sedum		1	0.1680	0.6825
Propagation		1	36.0429	<.0001
Soil		1	3.9530	0.0486
Sedum:Propagation		1	0.9000	0.3443
Sedum:Soil		1	0.0009	0.9757
Propagation:Soil		1	16.8799	0.0001
Sedum:Propagation:Soil		1	0.0162	0.8990

D) September 9: Avg. Heights	Trans	DF	F-value	P-value
Treatment	None			
Sedum		1	0.0238	0.8777
Propagation		1	91.6084	<.0001
Soil		1	0.7723	0.3809
Sedum:Propagation		1	1.9421	0.165
Sedum:Soil		1	0.0166	0.8975
Propagation:Soil		1	1.2838	0.2590

Sedum:Propagation:Soil		1	0.0434	0.8353

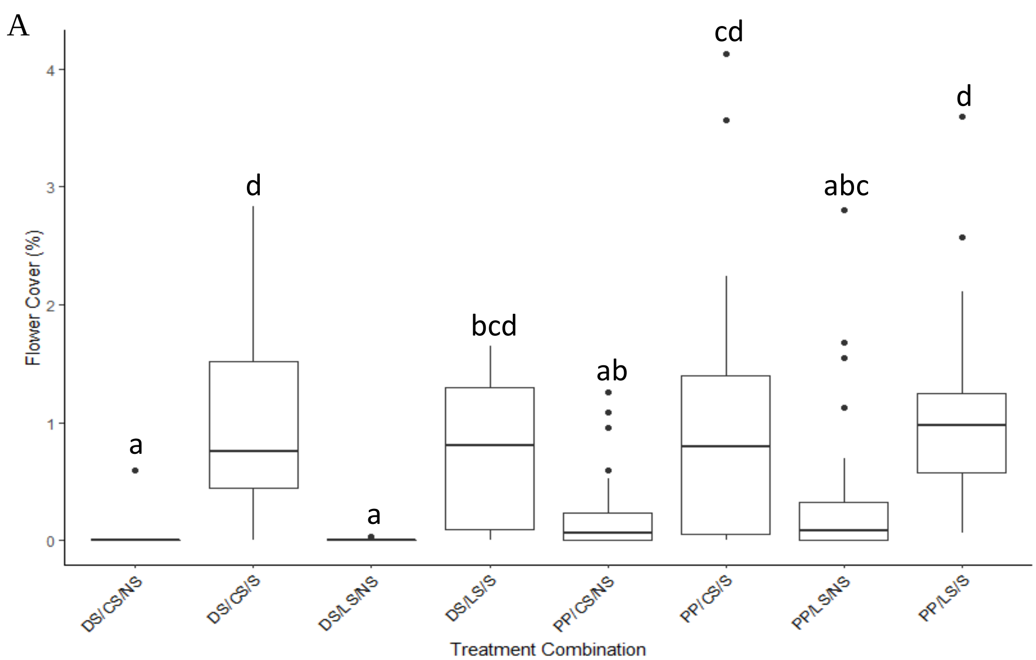
E) September 24: Avg. Heights	Trans	DF	F-value	P-value
Treatment	Tuky			
Sedum		1	11.605	0.0008
Propagation		1	94.378	<.0001
Soil		1	0.152	0.6972
Sedum:Propagation		1	0.104	0.7481
Sedum:Soil		1	0.020	0.8890
Propagation:Soil		1	0.155	0.6941
Sedum:Propagation:Soil		1	1.421	0.2351

<u>*4.4 Flower Cover*</u>

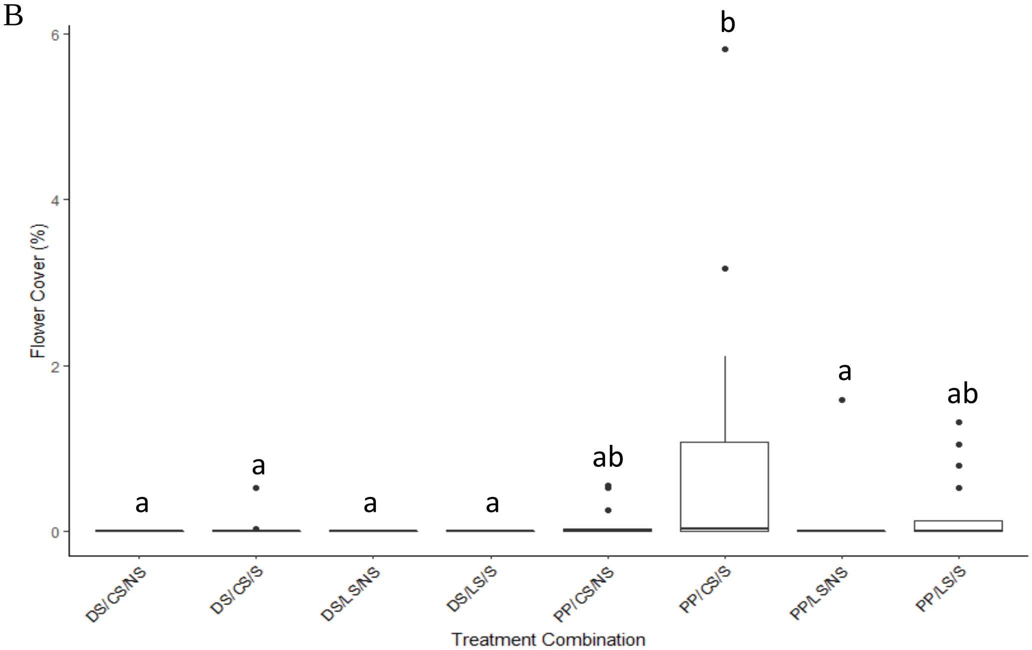
Average flower cover was recorded approximately every two weeks over the summer of 2020. On July 28, 2020, both *Sedum* and propagation had significant effects on flower cover (Table 9, A). *Sedum* had a higher percentage of coverage (Figure 14, A) and treatments including plug planting had higher flower cover as well. The treatment with the highest percentage of flower cover was PP/CS/S and PP/LS/S at 1.06 (± 0.201) % and 1.06 (± 0.194) % respectively. The treatment with the lowest coverage was DS/LS/NS with a mean of 0.00165 (± 0.00165) %.

On August 10, *Sedum* and propagation had a significant interaction effect on flower cover (Table 9, B). In the direct seeding treatment, there was no difference in flower cover between the *Sedum* treatments. However, in the plug planting treatment, there was higher flower cover in the modules containing *Sedum* (Figure 14, B). Lastly, soil was also found to have a significant effect on flower coverage (Table 9, B). Modules containing commercial soil had a higher flower coverage than the local soil. The treatment with the highest mean flower cover was PP/CS/S/ at 0.807 (± 0.326) % and the treatment with the lowest mean flower cover was DS/CS/NS, DS/LS/NS, and DS/LS/S with no flower cover present. On August 27, an interaction occurred between propagation and soil (Table 9, C). In the direct seeding treatment, flower cover was not affected by the soil type but in the plug planting treatment, flower cover was higher when local soil was used. The treatment with the highest mean flower cover was PP/LS/S at 1.00 ± (0.233) % and the majority of the direct seeding treatments had zero flower cover (Figure 14, C).

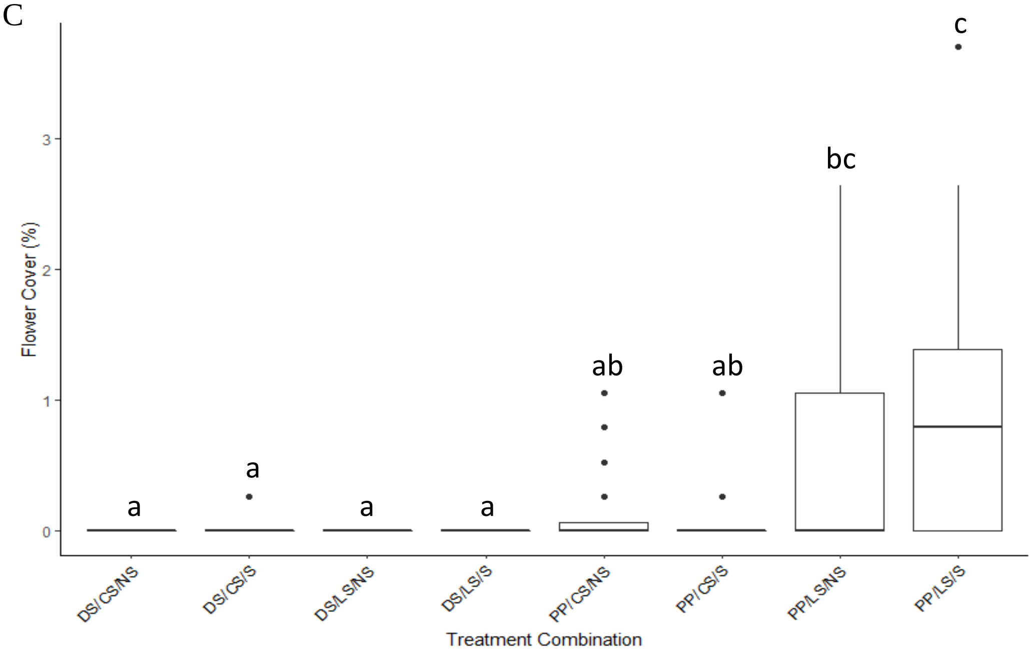
In September, both dates (Sep. 9 and Sep. 24) yielded a significant effect on flower cover from the propagation treatment (Table 9, D, E); plug planting yielded the highest flower cover. On September 9, the treatment with the highest flower cover was in PP/CS/S at 0.551 (± 0.340) % and the lowest was DS/CS/S with no flower cover (Figure 14, D). On September 24, the highest flower cover was found in PP/LS/NS at 1.02 (± 0.445) % (Figure 14, E).



B


b
a
ab
ab
a
a
a
a
6
4
2
0
Flower Cover (%)
DS/CS/NS
DS/CS/S
DS/LS/NS
DS/LS/S
PP/CS/NS
PP/CS/S
PP/LS/NS
PP/LS/S
Treatment Combination

C


c
bc
ab
ab
a
a
a
a
3
2
1
0
Flower Cover (%)
DS/CS/NS
DS/CS/S
DS/LS/NS
DS/LS/S
PP/CS/NS
PP/CS/S
PP/LS/NS
PP/LS/S
Treatment Combination

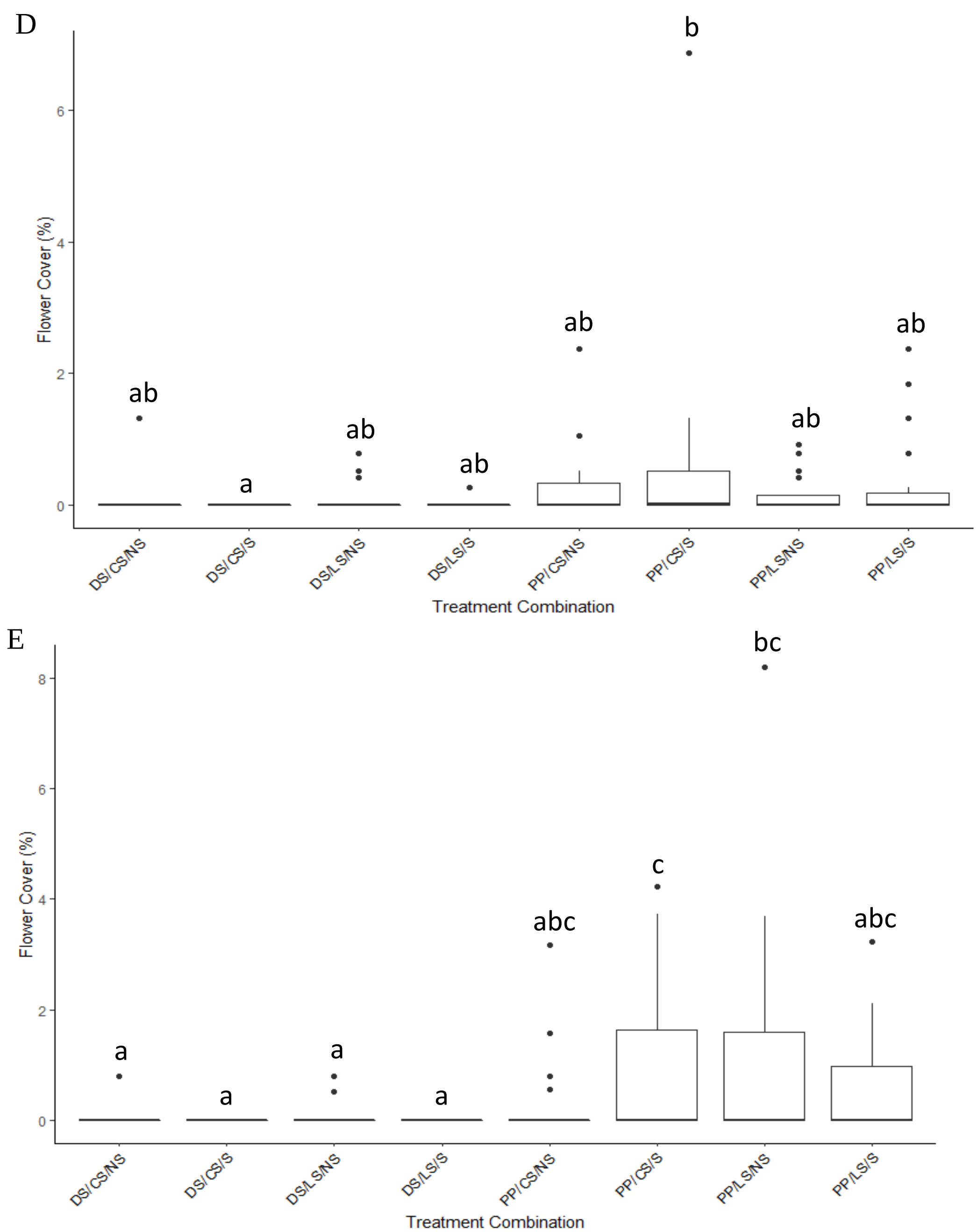


Figure 14. Average flower cover percentage for each treatment module for the summer of 2020 including: July 28, 2020 (A), August 10, 2020 (B), August 27, 2020 (C), September 9, 2020 (D), and September 24, 2020 (E). Boxes without shared letters are significantly different.

Table 9: ANOVA tables for each date of flower cover percentage including p-values for significance.

A) July 28: Flower Cover	Trans	DF	F-value	P-value
Treatment	Tukey			
Sedum		1	82.1588	<.0001
Propagation		1	6.8142	0.0100
Soil		1	0.0001	0.9923
Sedum:Propagation		1	3.2146	0.0750
Sedum:Soil		1	0.1912	0.6625
Propagation:Soil		1	2.9595	0.0874
Sedum:Propagation:Soil		1	0.6297	0.4287

B)August 10: Flower Cover	Trans	DF	F-value	P-value
Treatment	Tukey			
Sedum		1	7.80347	0.0059
Propagation		1	26.02053	<.0001
Soil		1	6.16038	0.0142
Sedum:Propagation		1	4.37707	0.0381
Sedum:Soil		1	0.34078	0.5603
Propagation:Soil		1	3.17084	0.0770
Sedum:Propagation:Soil		1	0.01382	0.9066

C) August 27: Flower Cover	Trans	DF	F-value	P-value
Treatment	Tukey			
Sedum		1	1.3978	0.2390
Propagation		1	50.8142	<.0001
Soil		1	15.7966	0.0001
Sedum:Propagation		1	0.9245	0.3378
Sedum:Soil		1	1.5729	0.2117
Propagation:Soil		1	17.6000	<.0001
Sedum:Propagation:Soil		1	2.1753	0.1423

D) September 9: Flower Cover	Trans	DF	F-value	P-value
Treatment	Tukey			
Sedum		1	0.0078	0.9299
Propagation		1	18.4388	<.0001
Soil		1	0.0134	0.9080
Sedum:Propagation		1	1.1721	0.2807
Sedum:Soil		1	0.0595	0.8076
Propagation:Soil		1	1.7405	0.1891
Sedum:Propagation:Soil		1	0.0096	0.9222

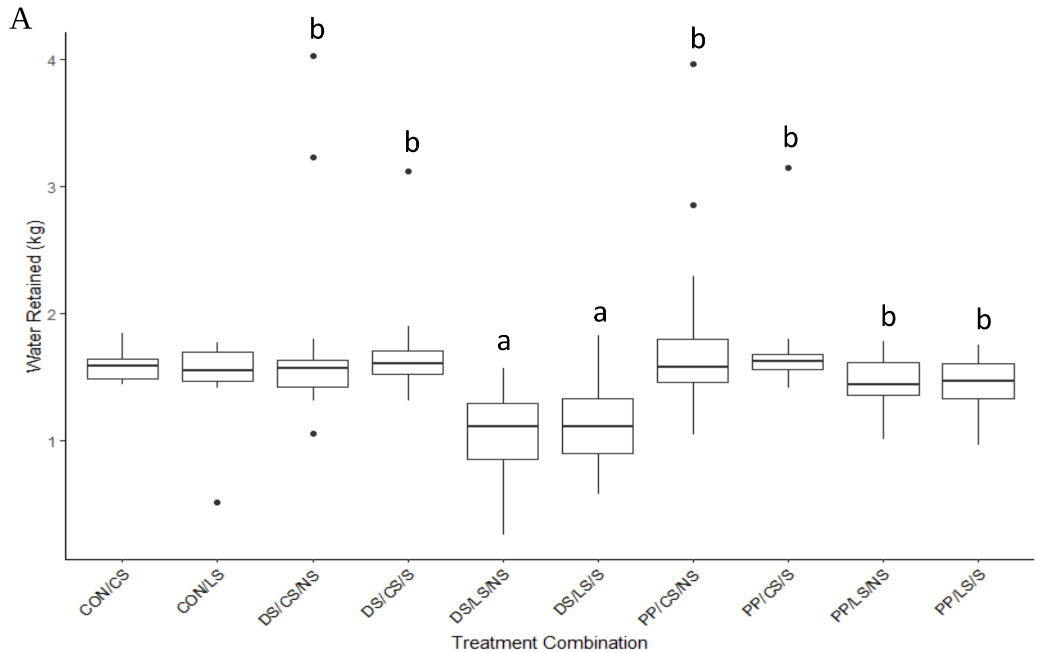
E) September 24: Flower Cover	Trans	DF	F-value	P-value
Treatment	Tukey			
Sedum		1	0.0772	0.7815
Propagation		1	28.1574	<.0001
Soil		1	0.3267	0.5684
Sedum:Propagation		1	1.3390	0.2491
Sedum:Soil		1	2.4647	0.1185
Propagation:Soil		1	0.1057	0.7456
Sedum:Propagation:Soil		1	1.7515	0.1877

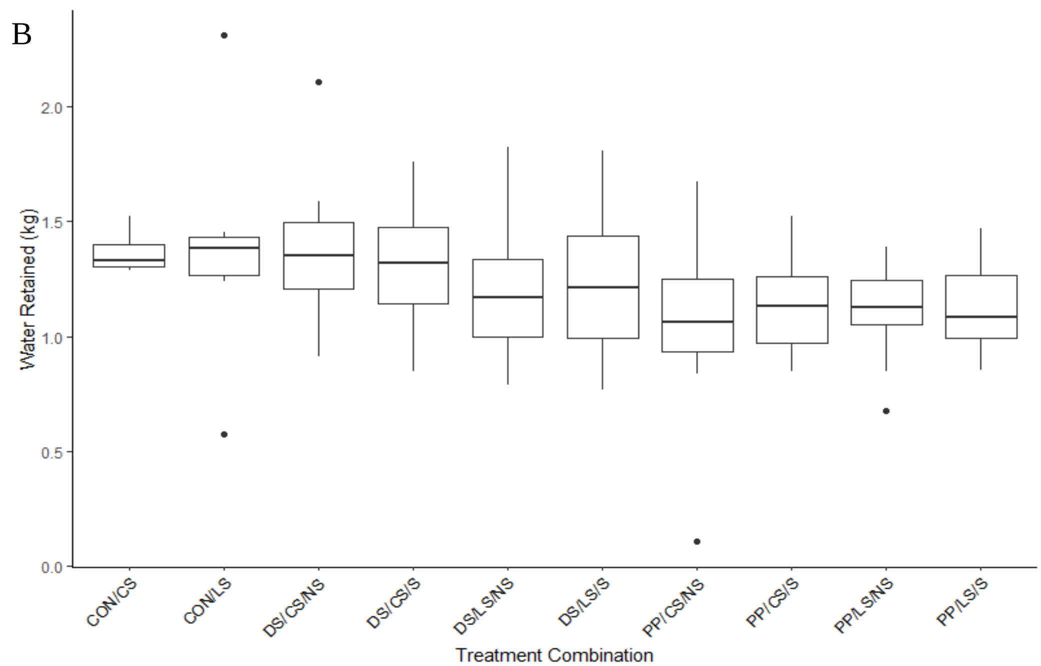
4.5 Water Retention

The amount of water retained was measured for each month during the summer of 2020. Block did not have a significant effect on water retention in any of the summer months. In July, treatment had a significant effect on the amount of water retained and plug planting resulted in greater stormwater retention than direct seeding especially when local soil was used (Table 10, A). However, direct seeding and plug planting did similarly well when the commercial soil was used. The treatment that held the most water was PP/CS/NS with a mean of 1.76 (± 0.145) kg and the treatment with the least mean water retained was DS/LS/NS at 1.07 (± 0.0736) kg (Figure 15, A).

In August, propagation had a significant effect on the amount of water retained, but soil and *Sedum* did not (Table 10, B). The treatments with direct seeding retained slightly more water than the plug planting treatments (Figure 15, B). The treatment with the most soil retained was DS/CS/NS at 1.36 (± 0.0932) kg and the treatment with the least retained water was PP/LS/NS at 1.12 (± 0.0387) kg.

Lastly, in the month of September, both propagation and soil had a significant effect on the amount of water retained in the soil (Table 10, C). Plug treatments with commercial soil retained the most water retained, and direct seeding with local soil had the least water retained (Figure 15, C). The control modules without vegetation also retained less water. The treatment with the most water retained were PP/CS/NS and PP/CS/S at 1.67 (± 0.0277) kg and 1.67 (± 0.0202) kg respectively.


A
b
b
b
b
a
a
b
b
4
3
2
1
Water Retained (kg)
CON/CS
CON/LS
DS/CS/NS
DS/CS/S
DS/LS/NS
DS/LS/S
PP/CS/NS
PP/CS/S
PP/LS/NS
PP/LS/S
Treatment Combination


B
2.0
1.5
1.0
0.5
0.0
Water Retained (kg)
CON/CS
CON/LS
DS/CS/NS
DS/CS/S
DS/LS/NS
DS/LS/S
PP/CS/NS
PP/CS/S
PP/LS/NS
PP/LS/S
Treatment Combination

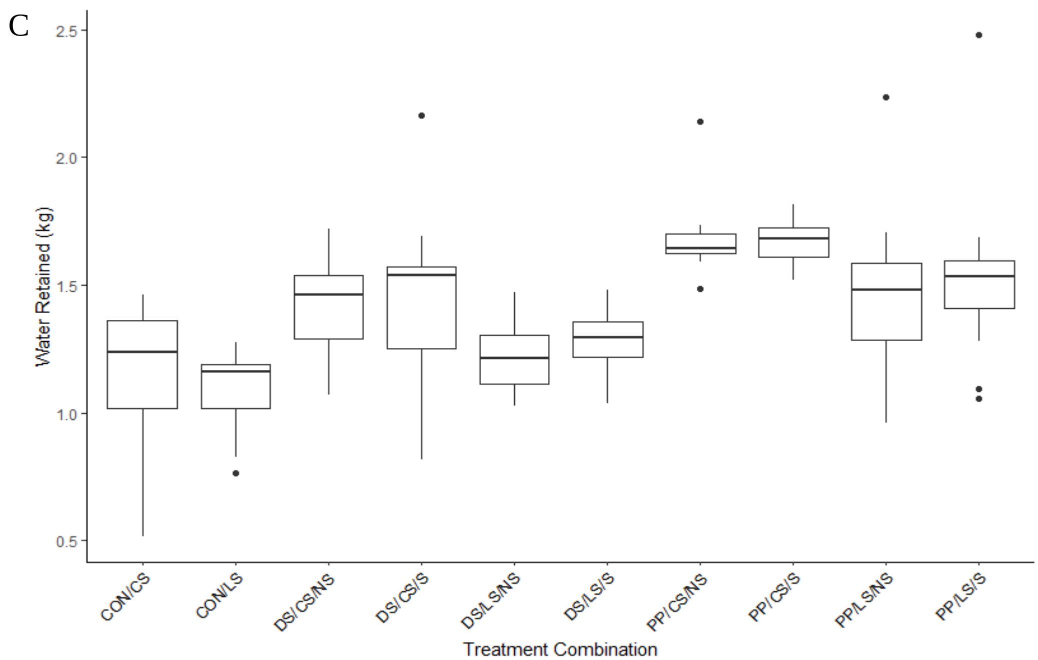


Figure 15. Box plot of water retained over the course of the summer in 2020 on July 22, 2020 (A), August 21, 2020 (B) and September 28, 2020 (C). Retention was measured by obtaining the air-dry weight of a module, then adding 2 L of water over a 30 second period. Modules were then left for 10 minutes and reweighed. Retention was calculated by subtracting the dry weight from the wet weight. Boxes without shared letters are significantly different. Boxes without any letters had no significance between treatments.

Table 10: ANOVA tables for each month of water retention including p-values for significance.

A) July: Retention	Trans	DF	F-value	P-value
Treatment	Tukey			
Sedum		1	0.0	0.9818
Propagation		1	15.9	0.0001
Soil		1	56.7	<.0001
Biomass		1	0.9	0.3299
Sedum:Propagation		1	0.3	0.5747
Sedum:Soil		1	0.0	0.8679
Propagation:Soil		1	14.1	0.0002
Sedum:Propagation:Soil		1	0.1	0.6627

B) August: Retention	Tran	DF	F-value	P-value
Treatments	Tukey			
Sedum		1	0.0333	0.8555
Propagation		1	18.8464	<.0001
Soil		1	2.0069	0.1586
Biomass		1	0.0407	0.8405
Sedum:Propagation		1	0.0954	0.7579
Sedum:Soil		1	0.0047	0.9453
Propagation:Soil		1	2.5533	0.1122
Sedum:Propagation:Soil		1	2.2569	0.1351

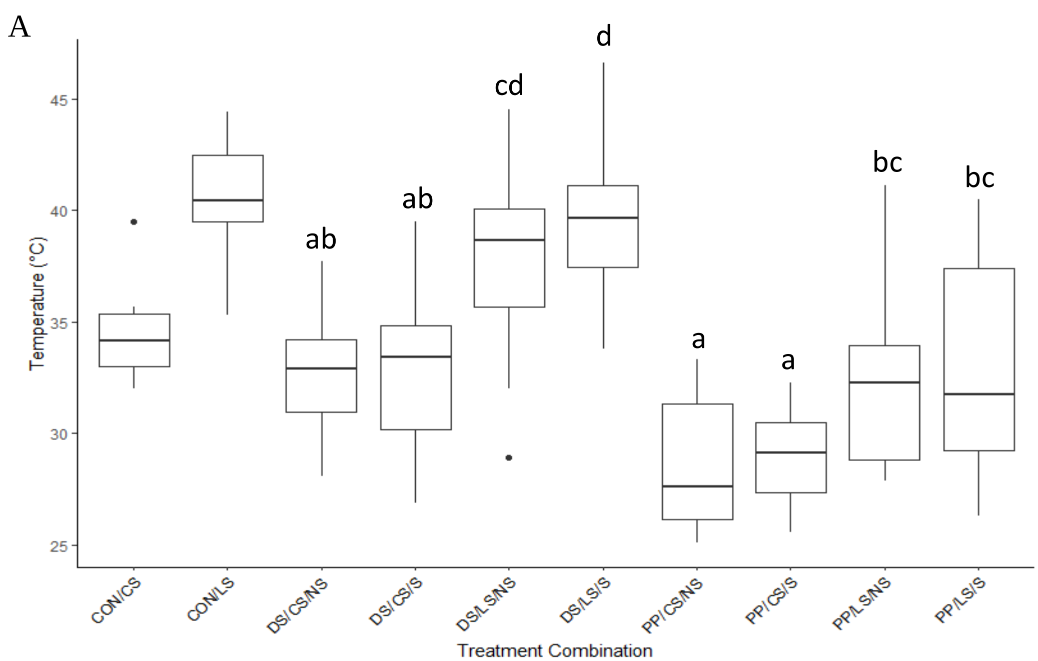
C) September: Retention	Trans	DF	F-value	P-value
Treatment	Tukey			
Sedum		1	1.828	0.1785
Propagation		1	61.182	<.0001
Soil		1	38.403	<.0001
Biomass		1	0.820	0.3667
Sedum:Propagation		1	0.447	0.5047
Sedum:Soil		1	0.726	0.3955
Propagation:Soil		1	0.001	0.9736
Sedum:Propagation:Soil		1	0.015	0.9012

4.6 Soil Temperature

In July, a significant interaction was found between propagation and soil type treatments (Table 11, A). The direction of this interaction indicates that commercial soil had lower temperatures than the local soil, and when paired with the plug planting propagation method, reduced the soil temperature even more. Due to the higher biomass in plug modules, this had a significant effect on lowering the temperature of the soil ($p = 0.0011$) (Table 11, A). The control treatments also had higher temperatures that most treatment modules (Figure 16, A). The treatment with the lowest soil temperature was PP/CS/NS at 28.5 (± 0.604) °C. The treatment with the highest temperature was the local soil control treatment at 40.6 (± 0.635) °C (Figure 16, A). Block had a significant effect on temperature in July ($p < 0.0001$) (Figure 17, A). The block with the highest temperature was block 2 with a mean of 36.8 (± 1.05) °C and the block with the lowest temperature was block 1 with a mean temperature of 31.0 (± 0.975) °C.

August produced a similar interaction between propagation and soil where commercial soil had lower temperatures than the local soil (Table 11, B). This difference was more dramatic in the direct seeding propagation method and became less dramatic in the plug method. Biomass had a significant effect on the temperature (Table 11, B) where the higher the biomass in a module, the lower the soil temperature. The treatment in August with the lowest soil temperature was PP/CS/NS and PP/CS/S at 25.9 (± 1.73) °C and 25.9 (± 0.619) °C. The treatment with the highest soil temperature was the local soil control at 34.6 (± 0.371) °C (Figure 16, B). Block had a significant effect on temperature in August ($p < 0.0001$) (Figure 17, B). The block with the highest temperature was block 2 with a mean of 31.9 (± 0.644) °C and the block with the lowest temperature was block 1 with a mean temperature of 27.4 (± 0.834) °C.

In September, biomass, soil type and propagation type had a significant effect on temperature (Table 11, C). When biomass is higher, the temperature of soil is lower and thus, most plug treatments did better than the direct seeding treatments (Figure 16, C). The local soil was found to have higher temperatures than the commercial soil. Control treatments hotter than most treatments. The treatment with the lowest soil temperature was PP/CS/S at 15.3 (± 0.244) °C and the soil with the highest soil temperature was the local soil control at 22.4 (± 0.277) °C. Block had a significant effect on temperature in September ($p < 0.0001$) (Figure 17, C). The block with the highest temperature was block 2 with a mean of 19.6 (± 0.671) °C and the block with the lowest temperature was block 1 with a mean temperature of 17.8 (± 0.626) °C.



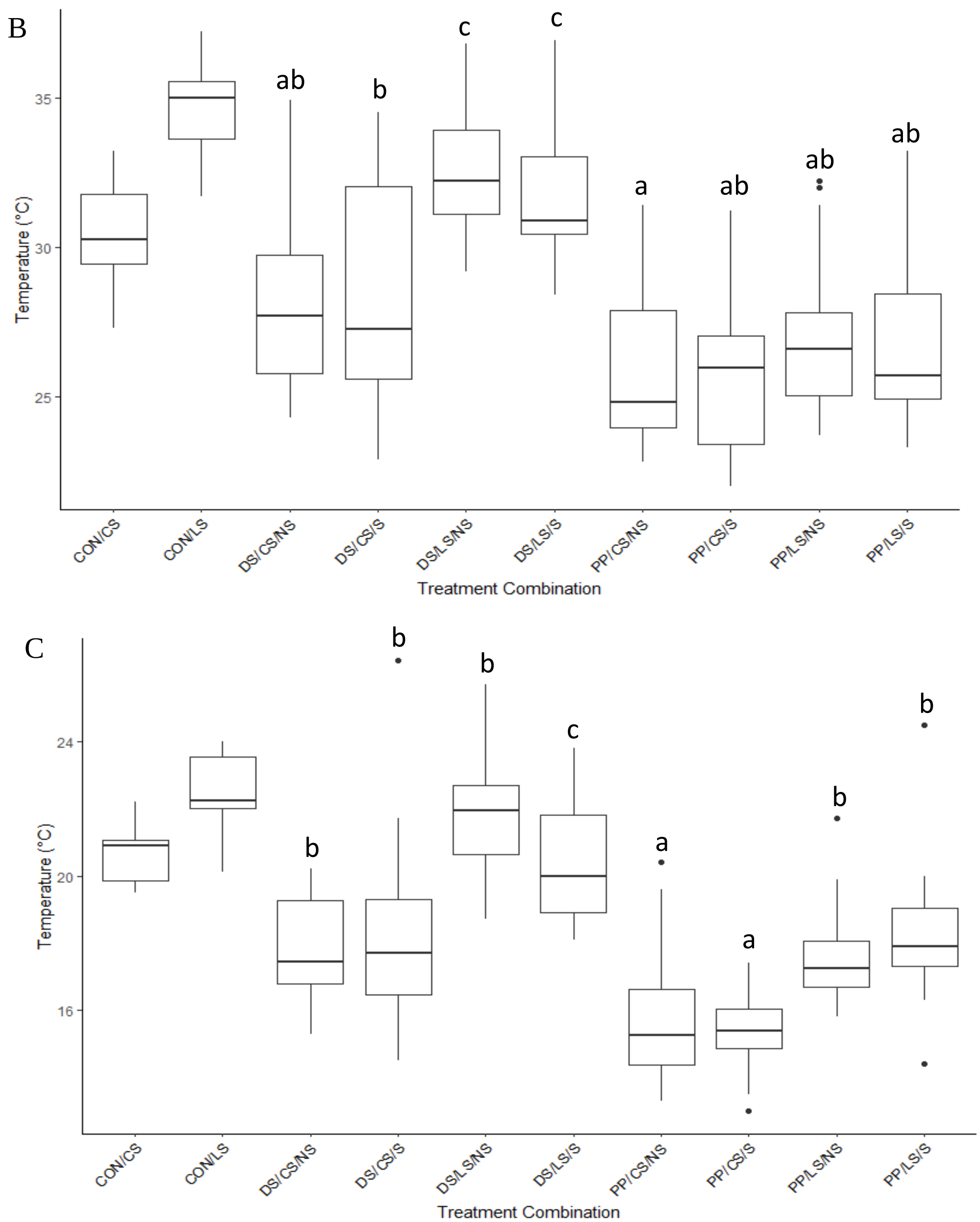


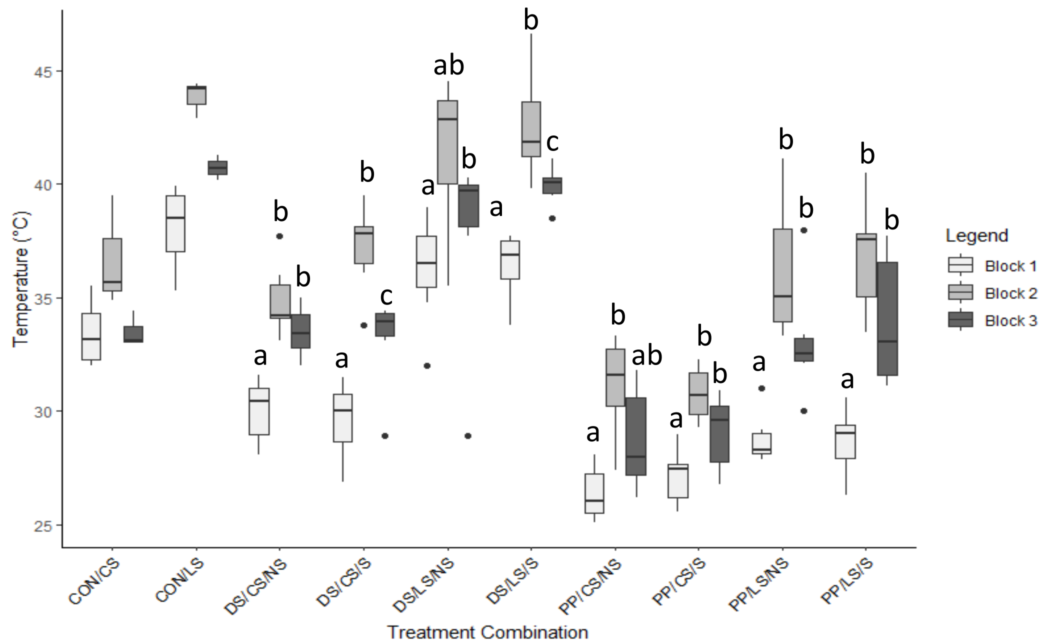
Figure 16. Box plots of soil temperature for the summer of 2020 on July 21, 2020 (A), August 17, 2020 (B) and September 28, 2020 (C). Temperatures were recorded with a temperature probe in each module. The probe was inserted into the bottom of the soil.

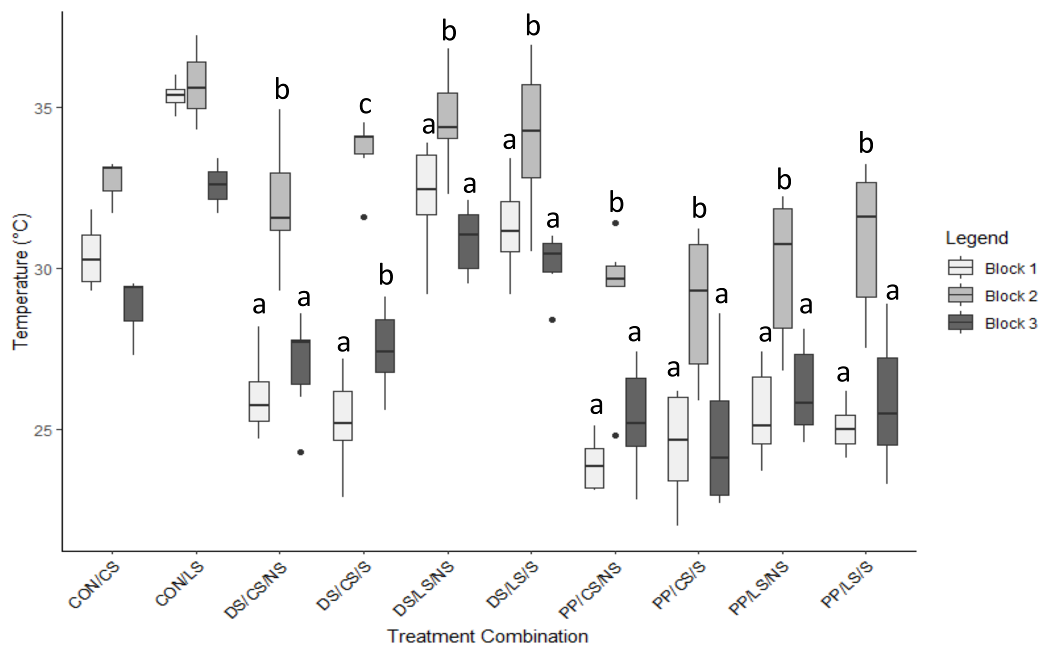
Table 11. ANOVA tables for each month of temperatures taken from modules including p-values for significance.

A) July: Temperature	Tuky	DF	F-value	P-value
Treatment	None			
Sedum		1	2.7222	0.1011
Propagation		1	245.0850	<.0001
Soil		1	221.3909	<.0001
Biomass		1	11.0994	0.0011
Sedum:Propagation		1	0.3973	0.5295
Sedum:Soil		1	0.0254	0.8736
Propagation:Soil		1	7.2469	0.0079
Sedum:Propagation:Soil		1	0.4641	0.4968

B) August: Temperature	Tuky	DF	F-value	P-value
Treatment	None			
Sedum		1	0.2404	0.6247
Propagation		1	163.0112	<.0001
Soil		1	74.3292	<.0001
Biomass		1	2.4950	0.1163
Sedum:Propagation		1	0.0081	0.9283
Sedum:Soil		1	0.9467	0.3321
Propagation:Soil		1	15.4423	0.0001
Sedum:Propagation:Soil		1	0.1194	0.7302

C) September: Temperature	Tran	DF	F-value	P-value
Treatment	Tukey			
Sedum		1	0.7159	0.3988
Propagation		1	118.9149	<.0001
WSoil		1	124.3634	<.0001
Biomass		1	7.2854	0.0078
Sedum:Propagation		1	0.0519	0.8201
Sedum:Soil		1	0.1439	0.7050
Propagation:Soil		1	0.0153	0.9016
Sedum:Propagation:Soil		1	3.4937	0.0636


Temperature (°C)
45
40
35
30
25
CON/CS
CON/LS
DS/CS/NS
DS/CS/S
DS/LS/NS
DS/LS/S
PP/CS/NS
PP/CS/S
PP/LS/NS
PP/LS/S
Treatment Combination
Legend
Block 1
Block 2
Block 3


Temperature (°C)
35
30
25
CON/CS
CON/LS
DS/CS/NS
DS/CS/S
DS/LS/NS
DS/LS/S
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PP/CS/S
PP/LS/NS
PP/LS/S
Treatment Combination
Legend
Block 1
Block 2
Block 3

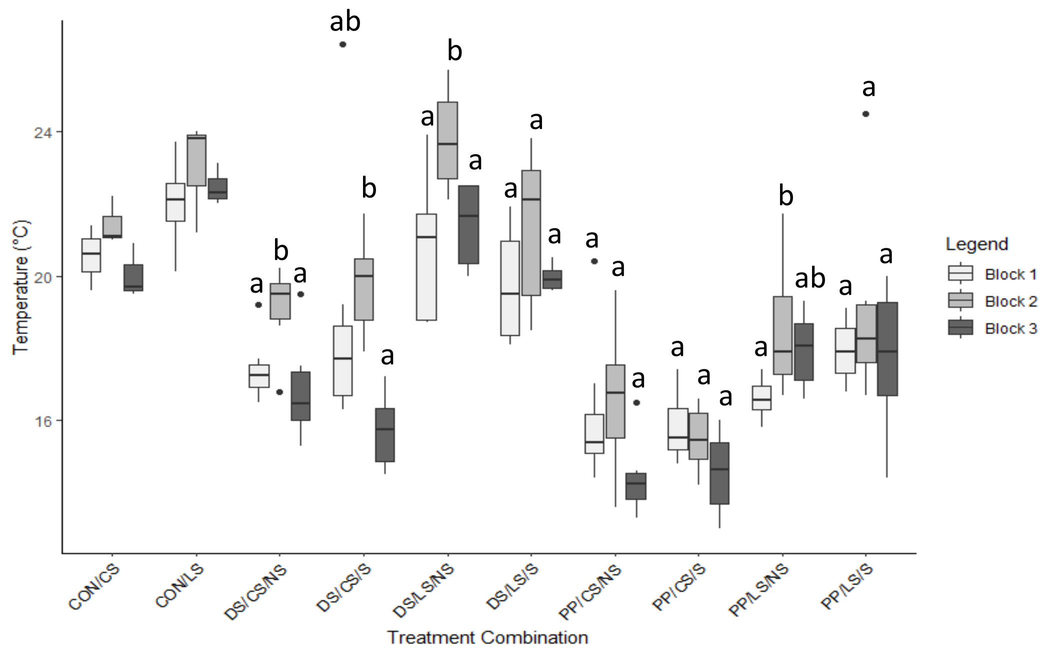

Figure 17. Block effect for temperature (°C) throughout the summer on July 21, 2020, August 17, 2020 and September 28, 2020.

4.7 Soil Nutrient Analysis

A soil and water analysis were conducted to determine the mineral component, pH, nitrogen and organic matter percentage in each of the soil treatments. Soil type had a significant effect on the mineral content in each of the soil treatments ($p<0.0001$).

Mineral content was measured from soil samples containing no vegetation on July 22. Results indicate that the commercial soil had higher nutrient contents in almost all minerals than the local soil (Table 12). The commercial soil had a lower pH than the local soil with an average of 7.49 (± 0.0618) and 8.13 (± 0.0.219) pH units respectively. Commercial soil had higher organic matter and nitrogen content than the local soil with an average of 6.67

(± 0.969) % organic matter and 0.313 (± 0.0733) % nitrogen. Local soil had an average of 1.13 (± 0.0333) % organic matter and 0.0233 (± 0.00664) % nitrogen.

Table 12. Growth media analysis conducted by The Department of Agriculture, Laboratory Services in Truro, Nova Scotia. Accredited methods used by the laboratory can be found in section *3.3.5.1 and 3.3.5.2* of this study.

Soil Nutrient	Units	Growth Media Mean and S.D.		F-value	P-value
		Commercial Media	Local Media		Tukey
Aluminum	ppm	476.0 ± 84.3	166.0 ± 7.22	53.2	0.0019
Boron	ppm	1.44 ± 0.07	0.5 ± 0.00	18.6	0.0125
Calcium	ppm	2771 ± 280	1827 ± 114.32	11.9	0.0261
Copper	ppm	2.88 ± 0.30	0.613 ± 0.03	19.6	0.0115
Iron	ppm	132.0 ± 2.8	96 ± 3.48	84.9	2e-04
Manganese	ppm	36.3 ± 1.9	38.7 ± 0.66	1.07	0.3590
Magnesium	ppm	374.0 ± 84.3	56.5 ± 2.26	22.9	0.0087
Sodium	ppm	97.7 ± 73.9	32.7 ± 1.20	22.96	0.0087
P2O5	ppm	633.0 ± 140.3	90.5 ± 8.66	36.2	0.0038
K2O	ppm	468.0 ±396.1	58.5 ± 4.77	4.68	0.0966
Sulfur	ppm	61.3 ± 18	6 ± 0.00	18.6	0.0125
Zinc	ppm	12.4 ± 2.35	9.22 ± 6.47	0.30	0.6124
Organic Matter	%	6.67 ± 0.9	1.13 ± 0.03	21.6	0.0097
Nitrogen	%	0.313 ± 0.07	0.0233 ± 0.01	41.5	0.003
pH	pH Units	7.49 ± 0.06	8.13 ± 0.02	42.1	0.0029

Water runoff samples were also taken from soil samples on July 22, 2020. Results showed that nutrient runoff concentrations were higher for most minerals in the commercial growth media (Table 13). However, calcium and sodium were found to be higher in the local growth media than the commercial growth media.

Table 13. Runoff analysis conducted by The Department of Agriculture, Laboratory Services in Truro, Nova Scotia. Accredited methods used by the laboratory can be found in section 3.3.5.2 of this study. Values for comparison were included from the Guidelines for Canadian Drinking Water Quality.

Water Nutrient	Units	Water Runoff Mean and S.D.		F-value	P-value	Guidelines for Canadian Drinking Water Quality
		Commercial Media	Local Media			
Nitrate	Mg/L	26.0 ±11.18	11.1±2.21	1.70	0.2288	45
Boron	ppm	0.032±0.03	0±0.00	1.00	0.3466	5
Calcium	ppm	36.1±3.64	50.0±3.46	7.69	0.0241	N/A
Copper	ppm	0.012±0.01	0±0.00	1	0.3466	2
Iron	ppm	0.06±0.04	0±0.00	2.48	0.1535	<0.3
Magnesium	ppm	8.59±2.43	5.18±0.67	1.76	0.2208	N/A
Manganese	ppm	0±0.00	0±0.00	0	0	0.12
Phosphorus	ppm	1.89±0.68	0.678±0.15	5.19	0.0521	N/A
Potassium	ppm	117.0±73.34	25.3±5.55	0.10	0.7591	N/A
Sodium	ppm	48.6±24.95	49.7±6.48	0.37	0.5558	<200
Sulphate	ppm	122.0±46.06	36.4±2.97	10.7	0.0113	<500
Zinc	ppm	0.054±0.03	0±0.00	5.00	0.0557	<5
pH	pH Units	7.10±0.12	8.03±0.17	22.4	0.0015	7-10.5

4.8 Cost: Monetary and Time

Monetary and time costs were recorded for each of the treatment to support the best combinations and methods in this study.

4.8.1 Direct seeding Vs. Plug Planting Method

Overall, direct seeding took less time than the plug planting method. The plug planting propagation method involved various processes including cleaning pots, transplanting multiple times and planting the final species into modules. In total, cleaning pots took 2 hours and 54 minutes (Table 14) and filling pots with soil including transplanting took 37 hours and 23 minutes (Table 15). Time to plant plugs into the appropriate modules what then recorded and added an additional 21 hours thus resulting in a total of 58 hours and 23 minutes (Table 16). The direct seeding method took 19.5 hours to count and distribute the seeds into the appropriate modules (Table 17).

Due to all pots being cleaned and reused from previous experiments, no purchase was necessary for pots and trays. Thus, the only cost for the plug planting method was the HP Promix soil used for initial planting which was $290.3 (Table 18). However, simple plastic pots can be purchased for as little as $20 for 100 pieces. Direct seeding had no monetary cost. Seed collection costs (time) from coastal barrens areas were not collected as both propagation treatments required seed collection.

Table 14. Preparation time for the plug planting methods beginning in September, 2020. Pots were first cleaned by soaking them in hot tap water for 5 minutes, then cleaned with bleach and rinsed. Pots were then filled with soil using a trowel.

Task	Time (min)
Cleaning initial 25x10 in trays	20
Cleaning 3x3 in pots (32)	36
Cleaning 5x5 in pots (96)	65
Filling initial 25x10 in trays with soil and seed	20
Filling (32) 3x3 in pots with soil	13
Filling (96) 5x5 in pots with soil	20

Table 15. Time taken to transplant seedling native species from the initial 25x10 in tray into 3x3 in pots. Pots were filled with soil, then three small holes were made into the soil using a sterilized, glass stir rod and the seedlings (including the root) were placed into the hole and covered with soil.

Number of Plants per pot	Species	Time taken to transplant
3	*D. spicata*	1 hour 3 mins
3	*F. rubra*	1 hour 10 mins
3	*S. novi-belgii*	1 hour
3	*O.biennis*	1 hour
3	*R. rosea*	1 hour 1 min
3	*L. multiflora*	45 mins
3	*S. tridentata*	52 mins
3	*P. maritima*	1 hour
3	*S. bicolour*	55 mins

Table 16. Time taken to transplant native species from the 3x3 in pots into their own 5x5 in pot. Pots were first filled with soil, then a trowel was used to create a hole in the middle. Plants were then transplanted to their own individual pots and filled with soil.

Number of Plants per pot	Species	Time taken to transplant
1	*D. spicata*	3 hours 25 min
1	*F. rubra*	3 hours 50 mins
1	*S. novi-belgii*	3 hours 2 mins
1	*O.biennis*	3 hours 16 mins
1	*R. rosea*	3 hours 20 mins
1	*L. multiflora*	2 hours 20 mins
1	*S. tridentata*	2 hours 47 mins
1	*P. maritima*	3 hours 27 mins
1	*S. bicolour*	3 hours 10 mins

Table 17. Total time taken to plant all native plant species for both methods. Plugs were transplanted into 160 modules and seeds were directly planted into their appropriate modules. Three people worked on planting plugs and direct seeding.

Task	Time
Time taken to plant plugs into modules	21 hours
Counting seeds (10 per species) and planted into modules.	19.5 hours

Table 18. Cost in dollars for each of the propagation methods.

Item	Cost ($)
Promix Hp for plugs (3)	290.3
Trays	0
Seeds	0

4.8.2 Local Soil vs. Commercial Soil Treatment

Although the commercial soil took significantly less time to distribute than the local soil, the monetary cost was more than the local soil. The commercial soil took three hours in total to distribute into the appropriate modules and only used one person, whereas the local soil took 24 hours to mix and distribute into modules and used help from three people (total 24 hours combined labour) (Table 19).

In total, the local soils monetary cost was $69.40 per ten modules (Table 21) after being calculated from individual bags of material (Table 20). Therefore, the total cost for all 90 modules of local soil was $624.65. The commercial soil from SOPREMA Inc. was $378 (42 bags needed at $9) (Table 22). Thus, the commercial soil was more cost effective monetary wise.

Table 19. Time taken to mix and distribute the two different soils to all 160 modules (plus the 20 control soils). Mixing and distribution took place from June 5 to June 12, 2020 and had three students working.

Soil time	Time
Local soil mixing and distribution	24 hours
Commercial soil distribution	3 hours

Table 20. Materials used for the local soil and costs per individual bag.

Material	**Cost**
Pea Stone	$6.99
Sand	$6.99
Perlite	$7.99
Compost	Free

Table 21. Cost of one batch of local soil. Total cost of one batch of soil can be multiplied by nine to produce the total cost of local soil.

Bags for 1 Batch	**Cost**	**Total**
5.5 peastone	6.99	$38.445
3 perlite	7.99	$23.97
1 sand	6.99	$6.99
		$69.405

Table 22. Cost of one bag of SOPREMA Inc. commercial growth media Sopraflor X™. Amount needed was calculated by determining the volume needed for the whole project. One bag of commercial soil is 25 L.

Commercial Soil	**Cost**	**Total**
1 bag	9.99	42 bags = $378

Chapter 5: Discussion

5.1 Plant growth

Treatment combinations had an effect on plant growth

The treatments with the most vigorous growth was seen in (PP/LS/S and PP/LS/NS) and was likely due to the advanced start by using previously grown plugs. Direct seeding treatments had a later start and therefore needed time to germinate and establish. Direct seeding was also delayed until July (COVID-19), a hotter time of year that is less than ideal for germination; the plants should ideally be planted in spring. When *Sedum* was included, more canopy density was achieved than if the native plants existed alone. Furthermore, their combination proved best for canopy density such that if the *Sedum*s outcompeted the native species, there may have been more comparable cover levels in both the plug planted and the direct-seeded treatments. So, while some competition may have occurred between the plugs and *Sedum*, it was not significant enough to reduce canopy cover. Some studies also show that *Sedums* can act as competitors during productive conditions and facilitators in hot, dry conditions (Bertness and Callaway, 1994; Butler and Orians, 2011). Green roofs often contain these harsh conditions and thus, facilitation from *Sedum* may occur on green roofs.

Local growth medium produced taller plants and higher canopy density, which may have been due to similarities with soils in barrens habitats where the native species used here are often found. The species used in this study, such as *P. maritima*, *S. bicolor* and *F. rubra* reside in shoreline rock crevices, where little soil accumulates and salt spray is frequent (Porter et al., 2020). They are commonly found along Nova Scotia's rocky Atlantic shore where soils result from weathering of granites into coarse mineral substrates. The local growth medium growth in this study closely resembles this type of soil as the sand component has coarser grains than the commercial growth medium. Similar to growth media in modules, these species also live in shallow soils that rarely exceed 10 cm in thickness. Moreover, coastal barren soil in Nova Scotia is nutrient poor (Porter et al., 2020) and the local growth medium had lower macronutrient concentrations than the commercial growth medium (Table 12, 13).

The high canopy density and tall plant height in direct seeding treatments with *Sedum* are due to the overwhelming growth of the *Sedum* species. *Sedum* species typically have creeping stems, form wide mats (Butler and Orians, 2011; Matsuoka et al., 2020) and dominate green roof communities when growth media levels are below 10 cm. Increased depths of growth media usually correlate to an increase of canopy density and creates shade that is unfavorable to *Sedum* species (Dunnett and Kingsbury, 2004; Heim and Lundholm, 2014; Orberndorfer et al., 2007). Consequently, the true effect of the direct seeding treatments in the present study was likely to give *Sedum* a head-start over native plants, leading to competitive exclusion. Nevertheless, research has shown that some green roof plant combinations will have a net positive interaction during unfavorable conditions and net negative interaction during favorable conditions (Soliveres et al., 2011). This suggests that *Sedum* species could facilitate the native plants when less shade is present and natives could facilitate *Sedum* species when canopy density is moderate, provided that *Sedum* is planted after seeds germinate when using the direct seeding method on green roofs (one month after direct seeding). This would give the native species a proper establishment period and reduce the possible competition between the native plants and *Sedum*s.

Tall plants can be beneficial to services provided by green roofs like storm water retention. Studies where stormwater capture was positively correlated with plant heights suggest this may be due to overall greater resource demand and water uptake (Lundholm et al., 2014). However, it is important to remember there may be disadvantages to having tall species (like the native plants used in this study) in green roof environments. They may be more susceptible to drought and population crashes from using up more resources (Lundholm et al., 2014) and outcompete other species. This study was only one growth season so it would be beneficial to conduct a longer study to better understand the relationship between height and long-term green roof functioning.

In the direct seeding treatments, commercial growth medium yielded better growth than local growth medium. (Figure 10). Seedlings often compete with the process of atmospheric drying for the fast-diminishing moisture of the top growth media layer. If the media dries out too quickly, the seeds will be unable to germinate (Hillel et al., 1972). Similarly, seeds may not germinate or survive if growth media slakes when wetted or forms a hard crust upon drying (Hillel et al.,, 1972). Due to the large size and weight of the pea stone aggregate in the local growth medium, the sand component often settled underneath. This may have acted as a hard crust layer, further preventing seedling growth.

In regards to plant growth, green roofs with a balanced mixture of short and tall plants might be most appropriate for stormwater retention; a roof with many tall plants may require supplemental watering to ensure that they survive through extended dry periods. If direct seeding is desired, *Sedum* cuttings should only be added after plants have had time to establish and should be combined with a high moisture growth media. If plugs are desired, then a growth media matching their natural habitat may be more beneficial. Proper testing must be used when constructing a local media and therefore should use a standard like the ASTM E2777 – 20 Standard Guide for Vegetative Green Roof Systems. ASTM E2399/E2399M Test Method for Maximum Media Density for Dead Load Analysis of Vegetative (Green) Roof Systems are also an important consideration to protect the integrity of the roof structure. Depending on the user, local medias may be a better option for smaller scale green roofs. Decisions regarding which establish method to use can be found in section 5.3.

5.2 Ecosystem Services

Roof conditions and context affected plant growth and ecosystem services

Block 1, which was on the library roof at Saint Mary's University and was sheltered on all sides of the green roof had more canopy density than the other two blocks which were more exposed (Figure 12). Block 2 and 3 had similar canopy densities overall but slight differences in their development; block 3 had the least canopy density in August and September and block 2 had the least amount of canopy density in July (Figure 12). Temperatures of the growth media were also affected by the block. Overall, block 2 had the highest temperatures and block 1 had the lowest temperatures (Figure 17).

Since block 1 was almost completely protected from excessive irradiance by neighboring walls, plants did not easily die off and their growth was not stunted. Block 1 modules were also installed overtop of existing grass (with a black tarp underneath to prevent roots from growing into the ground). These factors likely contributed to lower temperatures and therefore optimal growing conditions for the plants. The high canopy density likely caused additional positive feedbacks to reduce soil temperatures, as did the sheltering effects of the block. Block 2 saw the highest temperatures from the study; these high temperatures may be attributed to the high exposure of the atrium roof at Saint Mary's University. Since the two walls surrounding this block were dark, the albedo was low and increased heat from the sun. Typically, proposed techniques for green roofs include increasing albedo of the urban environment to reduce temperatures (Santamouris, 2014) with materials that are reflective rather than absorptive. The position of these walls may have further trapped this heat as there was minimal wind flow on this area of the roof. While block 1 had four walls for protection, the green roof area was much larger than block 2. Additionally, modules were not close to the surrounding wall in block 1, whereas block 2 modules were directly beside surrounding walls. Lastly, a large wall vent was located above the modules on one of the walls. This vent emitted warm air, thereby adding to the heat in this area. The last block, block 3, was entirely exposed to direct sun without any surrounding walls except for a safety guardrail. The direct sunlight increased the temperatures more than the block 3 roof, but not as much as block 2 as there was more wind flow. These results highlight the importance of external factors that should be taken into consideration when planning a green roof. Albedo, wind flow and building structures can add to the extreme heat caused by direct sunlight.

The high temperatures on these roofs appeared to impact canopy density as the block 1 roof had the greatest density, and lowest temperatures. Block 2 had the lowest density with the highest temperatures, and block 3, which was also much warmer than block 1, had comparable canopy density to block 2. Block effects observed in other green roof studies have also indicated higher temperatures occurring in areas with more direct sunlight and also slight effects from albedo as well (MacIvor et al., 2011).

Propagation and soil composition affected weed canopy density

Propagation method and soil affected the density of unplanted (weed) species for August and September (Figure 11). In both August and September, plugs greatly reduced the number of weeds present in each module. In August, when direct seeding was used, commercial growth medium produced more weeds than when local growth medium was used. This difference may be attributed once again to the higher moisture and nutrient content in the commercial growth medium. These factors are favorable for seedlings. For minimal maintenance, a 'tougher' (less fertile) soil may be more beneficial. Direct seeding treatments likely had more weed canopy density as there was more surface area available on the growth media and less shading than in the modules with plugs. In order to prevent unwanted species from taking over, supplemental weeding may be required if direct seeding is used as the establishment method.

It is important to note that while direct seeding took less time, both methods require seeds to be collected from the coastal barrens of Nova Scotia. Direct seeding would take more seed to distribute and therefore more time would be spent in the field collecting. While seeds were counted out for the direct seeding method in this study, this would not occur in most green roof establishment scenarios. Typically, seeds would be mixed with media and distributed onto the roof at time of construction (Toronto and Region Conservation Authority, 2016). This would drastically cut down on time as the plug planting method took 21 hours. Moreover, direct seeding also costs less financially as there are no additional growing materials needed, no greenhouse rental and no extra soil. If instant greening and ecosystem services are desired, it would be more beneficial to use plugs but if saving on costs is desired, then direct seeding should be used.

Although both methods are acceptable, both also had negatives. Plugs are often harder to fill in and do not achieve full greening until two to three growth seasons (Buist, 2020). With direct seeding, full cover is usually achieved after one growth season (Toronto and Region Conservation Authority, 2016). However, based on results from this study direct seeding should not be planted at the same time as *Sedum* cuttings to prevent competition.

Treatment combination had an effect on flower cover

Overall, plug treatments had higher flower coverage than the direct seeding treatments (Figure 14). Since the plugs were already established, they flowered earlier than the direct seeding treatments, which had not yet established. Additionally, plugs had higher floral cover in local growth medium.

Similar to plant growth, these results could be an indication that the local growth medium was a closer resemblance to their original habitat in the coastal barrens of Nova Scotia. Micronutrients in soil (growth media on green roofs) can interact with other nutrients to form insoluble compounds and thus become unavailable for the plants to use. Therefore, the native plants are adapted to low nutrient levels, and thus, may be negatively impacted by the high nutrient levels of the commercial growth medium. For example, in situations where phosphorus is high, it can depress zinc uptake and the excess of potassium can also reduce the uptake of magnesium (Singh et al., 1986). Using this example, it may be possible that the high macronutrient levels in the commercial growth medium are limiting the uptake of some other important micronutrients. Zinc can be responsible for stem elongation, leaf expansion and chlorophyll production (Lines-Kelly, 1970). It is also important for protein synthesis, energy production and maintains the structural integrity of biomembranes. Deficiencies may inhibit seed development and cause delayed maturity and may ultimately impact flower production (Shukla et al., 2009). It is possible engineered commercial media may be limiting an important nutrient needed for flower production. Additionally, phosphorus is harmful to life forms like mycorrhizal fungi which enhance absorption of nutrients by plants (Singh et al., 1988).

When direct seeding was used, treatments did best with *Sedum* added; *Sedum* plants added flower cover when the native plants had not yet grown. Species of plants that flower at different times can improve the aesthetic appeal and also provide additional resources for pollinators throughout the growth season (Cook-Patton and Bauerle, 2012). Studies show that there are obvious differences in the timing of flowering existing between native plant species and traditional *Sedum*s on green roofs in Atlantic Canada (Heim and Lundholm, 2016). For example, *Rhodiola rosea* and *Solidago bicolor* experienced flowering through late summer into September while *S. acre* flowered mainly at the beginning of the summer (June – July) (Heim and Lundholm, 2016). Mixing all these species would provide longer flower cover throughout the growth season compared to *Sedum* only green roofs. *Sedum* had more flower cover in July and early August (Figure 14, A, B) but not in late August and September. However, propagation method had flower cover across all five dates (Figure 14, C, D, E). This may suggest that the natives provided flowering over the whole growth season while the *Sedum* provided cover from July to early August.

Bees are likely to benefit more from green roof flower cover than other insect species because they are able to forage vertically between the ground level and green roof (Braaker to al. 2014, MacIvor et al, 2014). Studies show that by using *Sedum* species on green roofs, both exotic bees and native bees benefit from their addition. Pollen loads from *Sedum*s have been observed to be relatively high in exotic bees compared to native bees, however, native bees also benefit due to the alternative option: a concrete building with no pollen. Additionally, native bees observed on green roofs with *Sedum* had significantly greater numbers of non-*Sedum* pollen types. This indicates that they may have been attracted by the abundance of *Sedum* flowers but continued to visit other flowering species on the green roof (MacIvor et al. 2014). This evidence supports the combination of *Sedum* and native plants species as they provide beneficial flower cover to bee species on green roofs.

To maximize floral cover on green roofs, users will benefit from including *Sedum* in addition to native plant species. To achieve this ecosystem service immediately, users should use plugs. Otherwise, the *Sedum* should be planted later than directly seeded native species to prevent competition. Users would also benefit from using a soil that closely matches the native species' habitat.

Commercial soil and plug planting improved water retention and growth media temperature the most

In this study, the commercial growth medium did best at water retention as the grain size of the sand used in the local growth medium was likely too big (Figure 15). While Sopraflor X™ uses sand, the grain size was significantly finer than the sand used in the local growth medium.

Other properties of the commercial growth medium likely contributed to the large amount of water retained, including the use of peat compost. The commercial media used in this study does contain a percentage of peat in the organic matter component but it is unclear how much. Municipal composting systems contain the full spectrum of organic wastes consisting of food scraps, animal waste, roadkill, biosolids, etc. While still useful in the retainment of water in growth media, the structure is different from peat moss which is primarily used for soil aeration. Due to the structural differences, water storing capabilities from the commercial media were likely aided by the use of peat compost. Although peat does well at storing water in growth media, there are still negative impacts associate with its use such as significant greenhouse gas emissions (Parish et al., 2008), habitat destruction (Mazerolle, 2003; Poulin, Rochefort, & Desrochers, 1999) and increased volume and duration of runoff in peat mining areas (Ballard, McIntyre, & Wheater, 2012; Holden et al., 2006; Robinson, 1985).

While there was a small increase in retention from direct seeding to plug planting in the commercial growth medium, there was a large difference between the plug method and direct seeding method in the local growth medium. One reason for this could be due to the use of mycorrhizal inoculation from the soil used to initially grow the plugs in. While an attempt was made to clean soil off the root structures of the plants, full removal was impossible to protect root integrity. One study shows that inoculated soil contains better aggregation, pores and higher saturated hydraulic conductivity than soil without mycorrhiza (Thomas et al. 1986).

When selecting a growth medium for water retention capabilities, based on this study it would be best to opt for the commercial soil using the plug propagation method. However, it is important to consider all aspects such that the use of peat and silt are still considered environmentally unfriendly. Peat contributes to the emission of greenhouse gasses and silt is not a non-renewable resource. Therefore, by using the local medium from this study as a framework that can be built upon, other measures can be taken through careful selection and consideration. Since silt is not typically obtained as a recycled material and is harvested from natural areas, it may be best to pair it with municipal compost, mycorrhizal inoculation and an arid recycled aggregate like brick. These amendments may make up for the elimination of peat because their greater water retention and lighter weight will improve porosity, thereby achieving similar results that including peat would achieve.

The temperature of growth media is also largely determined by media composition. Growth media that is able to retain water well will be lower in temperature than dry growth media. The finer sand grains and the ability to hold more water may be responsible for reducing the heat in the commercial growth medium. The local growth medium was not able to hold water as much water and dried up more quickly and thus had a lower ability to cool the surface via evaporation.

In September, higher canopy density resulted in lower growth medium temperatures. This is supported by various other green roof studies (Oberndorfer et al. 2007; Blanusa et al., 2012). In some cases, the direct seeding treatments with commercial growth medium were comparable to the plug treatments with local growth medium (Figure 16, B) indicating the type of soil also makes a large difference in the temperature. Similarly, some commercial growth media controls were lower in temperature than treatments containing vegetation and local growth medium. For lowest soil temperatures the plug method should be combined with a good water-storing growth media.

5.3 Practical Considerations

Soil composition and structure affected nutrient concentrations and leaching

When comparing nutrient concentrations, it is clear there were differences between the local and commercial growth medium. The local medium had lower concentrations of most nutrients than the commercial growth medium. (Table 12, 13). Because of this, nutrient uptake may have been affected. While low-nutrient media are desired to minimize nutrient leaching, the plants will need to have the appropriate nutrients for multiple growth seasons. In green roof systems, it is common for concentrations to decline by the leaching process whereby nutrients are flushed out from the growing medium over time (Van Seters et al., 2000). Since concentrations started out low for the local growth medium, future growth seasons will have lower concentrations, thus imposing problems for plants in the future eventually causing species to die off.

No clear guidelines regarding nutrient concentrations in runoff exist in Atlantic Canada. Additionally, the CCME (Canadian Council of Ministers of the Environment) guidelines: Canadian Water Quality Guidelines for the Protection of Aquatic Life indicate no available data for the nutrient concentrations used in this study. However, other green roof studies report similar nutrient concentrations in runoff; e.g. nitrate, where concentrations range from 0.2 to 22.7 mg/L (Berndtsson et al., 2009) and phosphorus with an observed range of 0.6 to 1.4 mg/L (Toland, et al. 2012). Information regarding Canadian Drinking Water Quality Guidelines (Table 13) should only be used for reference and general information since runoff from green roofs would not be fit for consumption. More accurate comparisons FLL guidelines regarding phosphorus, potassium, and magnesium are likely to be the most important due to their abundance in organic material. According to the FLL guidelines, nutrient content in growth media should be kept as low as possible. Nitrogen, phosphorus, potassium and magnesium should be kept under 80, 50, 500 and 200 ppm respectively (Table 23).

Table 23. Growth media nutrient recommendations provided by the FLL guidelines in Germany.

Soil Nutrient	Commercial (ppm)	Local (ppm)	Recommended by FLL guidelines (ppm)
Phosphorus	633.0	90.5	<50
Potassium	468.0	58.5	<500
Magnesium	374.0	56.5	<200

Due to the lack of clear information regarding runoff water quality in Nova Scotia, it would be best to select a growth media that has low runoff nutrient concentrations and align with the FLL guidelines. This would protect the integrity of nearby groundwater and marine systems. If vegetation on green roofs are noticeably lacking nutrients (i.e. wilting vegetation and yellowing stems), supplemental fertilization may be applied. According to the FLL guidelines, acceptable applications include coated NPK slow-release fertilizer capsules at a rate of 5 g N/m^2. Under no circumstances are herbicides to be used.

As the use of green roofs becomes more common in Atlantic Canada, future studies should focus on acceptable runoff concentrations from green roofs. Especially concentrations of nitrogen, phosphorus and potassium from organic matter used in growth media. Nutrient retention is also dependent on water retention (as total export of nutrients is the concentration times the volume of water runoff). This should be taken into consideration when attempting to limit nutrient concentrations in runoff. Water and nutrients are stored in the growth media and the drainage composite (Carpenter et al., 2016). Therefore, proper water retention properties in growth media are essential for limiting leaching.

It is important to follow guidelines and acknowledge the phenomenon of nutrient leaching from green roof growth media as they can affect downstream ecosystem processes such as increasing excess algae and plant growth in rivers and streams (Van Seters et al., 2009). However, green roofs typically have more benefits than conventional roofs where often zinc, lead and copper are higher as they are produced from coal tars and pitches from roofing shingles (Clark et al., 2002; Van Metre and Mahler, 2003).

Propagation method and growth media type differed in terms of time and monetary costs

The commercial growth medium took significantly less time to distribute than the local growth medium (24 vs. 3 hours) (Table 19). Unfortunately, due to the COVID-19 pandemic the materials for the local growth medium were mostly purchased through local retailers in bags instead of purchased in bulk from recycled materials. The idea is that these materials can be reused and local so no additional negative environmental factors contribute to climate change (e.g., fuel from transporting green roof growth media from Quebec). In this situation, the commercial growth media cost roughly $380, while the local growth medium cost $624 to make (Table 21, Table 22). Therefore, commercial growth medium did best cost wise (monetary and time). If the soil does not perform properly, the argument could be made that it is not more environmentally friendly. While the commercial growth medium came from Quebec and would have used more fuel to get to the Atlantic provinces, the local growth media in this study may provide insufficient nutrients for plants in the future, resulting in plant death and/or reconstruction of the green roof. The local growth medium in this study will need to become more cost-effective and better at sustaining plant growth in order to be a viable low-impact alternative to commercial growth medium.

If the growth medium were to be redesigned with readily available recycled materials, some better aggregate options other than peastone may be broken tiles, slag and foamed glass. Some other options include lava, pumice, expanded clay and expanded slate (FLL guidelines, 2002), however these options often do not originate from recycled materials and therefore brick may be a better option. Tests including water permeability, water storage ability and air content should be performed before installation by an institution where FLL guidelines are followed or ASTM standards. Generally, water permeability for extensive green roofs should be 0.6 – 70 mm, water storage ability should be greater than 35% but lower than 65% to avoid water logging and air content should be no less than 10% when the growth media is fully saturated.

According to the Regional Centre Land Use By-law (2019), flat roofs that are not exempt from site plan approval (section 16) shall provide soft landscaping (green roof) on at least 40% of the area of that roof. For purposes of calculating budgets, this table will be calculated based on a 20,000 sq ft roof. Therefore, 8000 sq ft of the roof structure shall be soft landscaping/green roof.

$$\mathbf{8000}\ \boldsymbol{ft^2} \times \mathbf{0.295}\boldsymbol{ft} = \mathbf{2362.064\ ft^3} = \mathbf{66886.2\ L}$$

Commercial growth media: $9 for 25 L

$$\frac{\mathbf{66886.2}}{\mathbf{25}} = \mathbf{2676\ bags\ of\ commercial\ growth\ media}$$

$$\mathbf{2676\ bags} \times \$\mathbf{9} = \$\mathbf{24,084}$$

The total cost for an 8000 sq ft green roof would be roughly $24,084 using the commercial growth media. This would not include the cost of installation and labour.

Local growth media:

Since the local growth medium in this project was more expensive than the commercial growth medium, it will not be compared monetary wise on such a large scale. Realistically, local growth media would be made from recycled materials from other landscaping businesses in the area which would be free or at a reduced price. Therefore, the majority of the cost would come from hiring green roof installers and growth media mixers. The price of labour in this scenario may be higher than that for the commercial growth medium since extensive work would go into mixing the soil. On a green roof of this scale, machines would be required to mix the soil. In this case, local growth medium may be more appropriate for smaller scale green roofs.

This study compared important green roof materials and methods including growth media selection, plant selection and establishment method selection. Table 24 indicates possible scenarios including budget, time restrains, and ecosystem service selection and which mixture should be used for the best fit.

5.4 Conclusion

This study outlines the most effective plant mixtures, growth media and establishment methods for use on green roofs in Atlantic Canada. Engineering an effective green roof growth medium is extremely challenging and requires rigorous testing to be used on a large-scale basis. This study was a good starting point for the construction of a local growth media in Atlantic Canada but due to limitations, lacked recycled materials, driving up costs. In future experiments once the local growth media is fine-tuned with the addition of porous aggregate and a silt component, testing from the ASTM should be used. Then, construction of a locally made growth media would is expected to prove superior to commercial media sourced from out of province, at least for a small-scale green roof. Overall, the commercial growth medium proved best as it had higher stormwater retention, weighed less, had lower growth medium temperatures and was cheaper. The propagation technique that had the best results was the plug planting method combined with the addition of *Sedum*. Landscape architects, researchers and other green roof users should refer to Table 24 for an analysis of possible scenarios that would be beneficial when selecting plant mixtures, growth media and propagation techniques.

Table 24. Scenarios for potential landscape architects when considering which combinations of growth media, plant selection and establishment method to use.

Scenario	Growth Media	Plant Selection	Establishment Method
High budget, tight time restraints, moderate ecosystem services, environmentally friendly (low)	Commercial growth media	*Sedum*	Direct seeding
Low budget, no time restraints, maximum ecosystem services immediately, environmentally friendly (high)	Local growth media tested with ASTM standards	Native Plant/*Sedum* mixture	Plug
High budget, moderate time restraints, maximum ecosystem services, environmentally friendly (moderate)	Commercial growth media	Native plant/*Sedum* mixture	Direct seeding
Low budget, moderate time restraints, maximum ecosystem services, environmentally friendly (high)	Local growth media tested with ASTM standards	Native plant/*Sedum* mixture	Direct seeding
Low budget, tight time restraints, moderate ecosystem services, environmentally friendly (low)	Local growth media with ASTM standards	*Sedum*	Direct seeding

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Table 1 References

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Appendix

Supplemental Interaction Plots

Canopy Density

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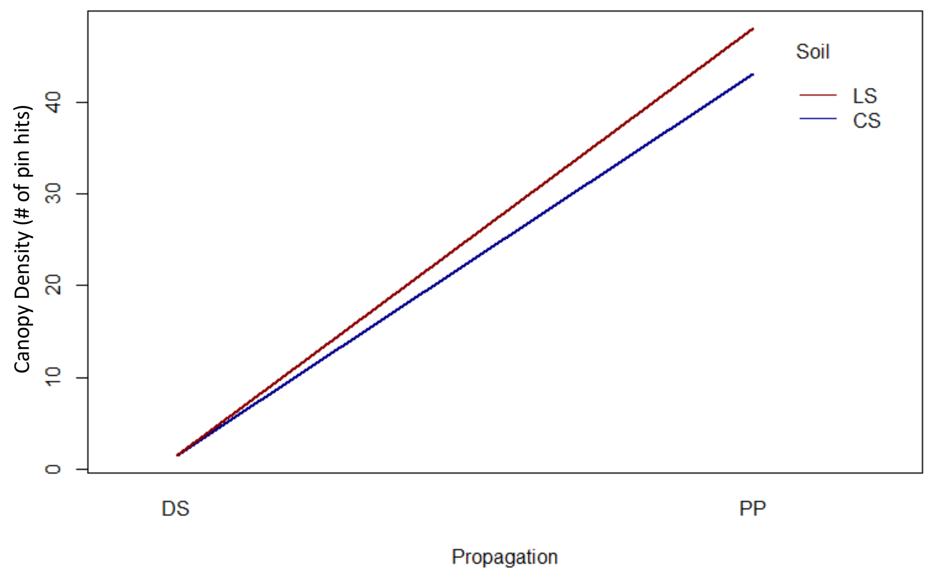
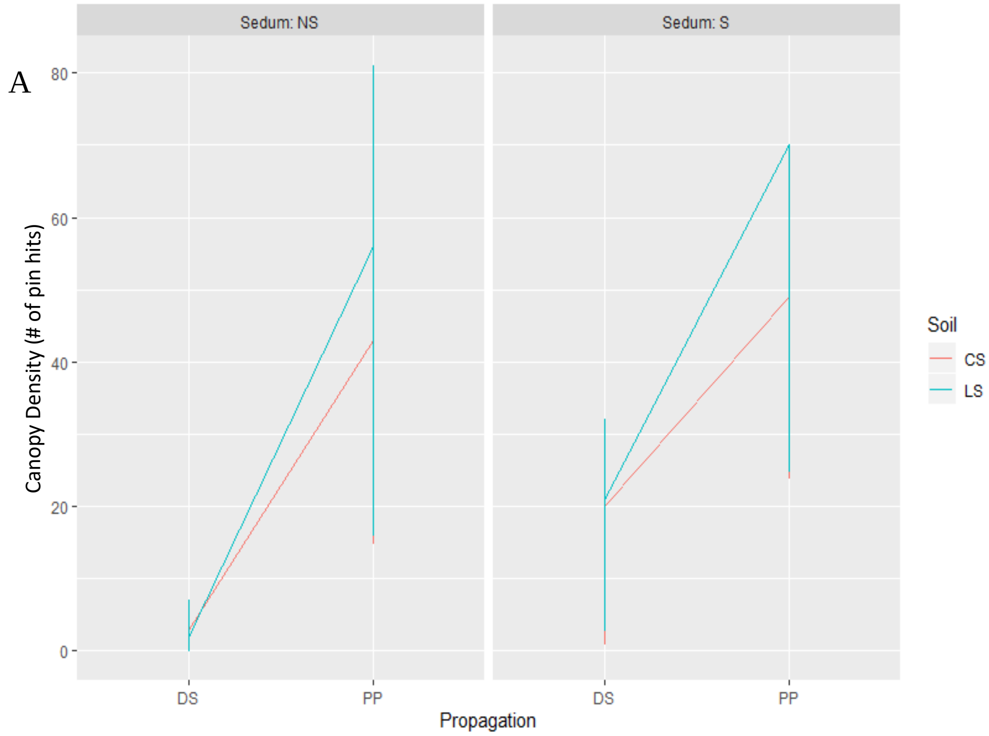
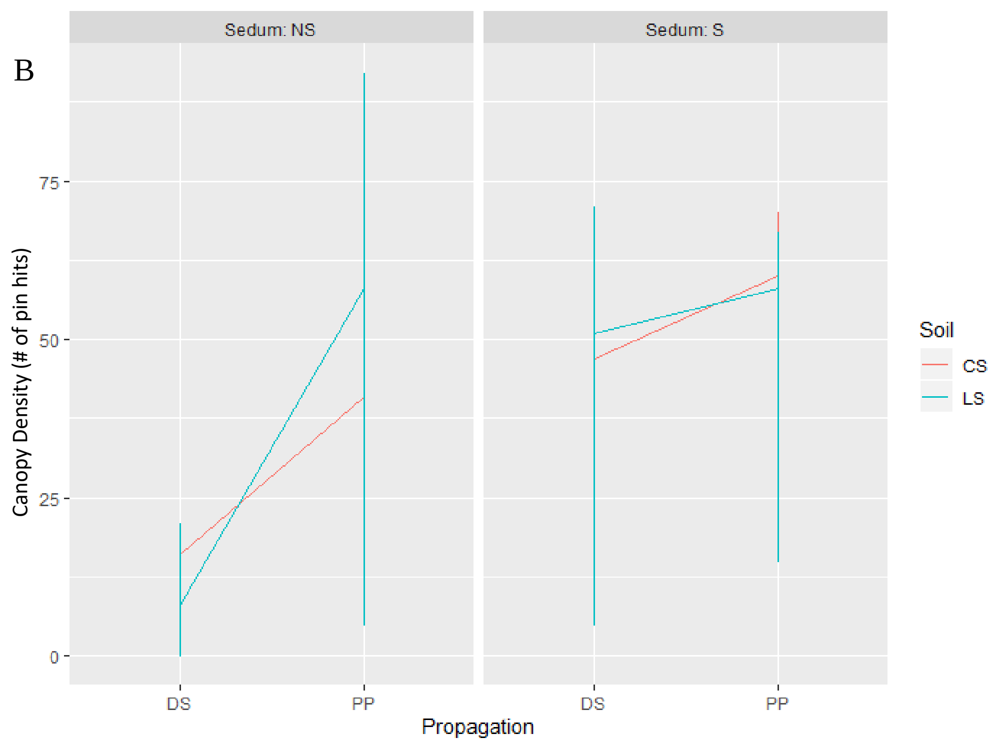
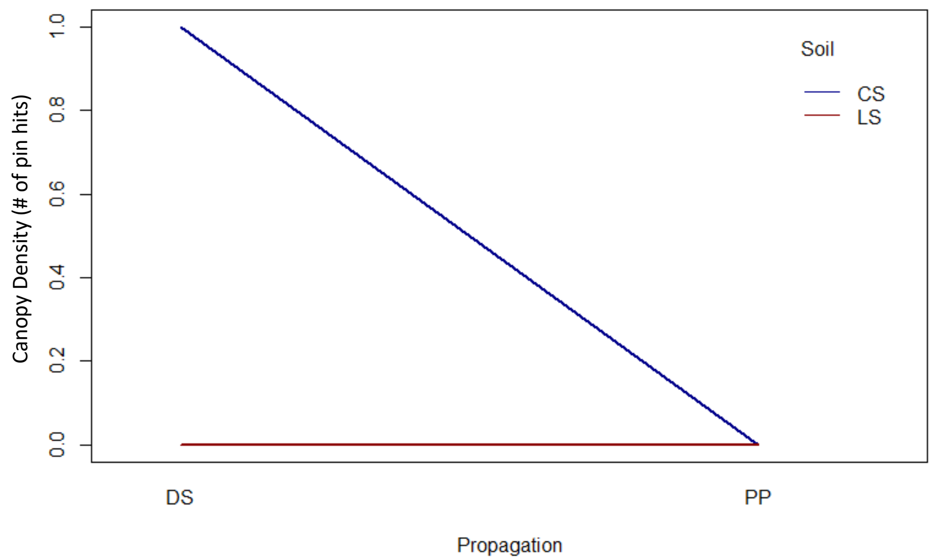


Appendix A. Plot showing the significant two-way interactions occurring between propagation/soil for estimated biomass in July 20, 2020.





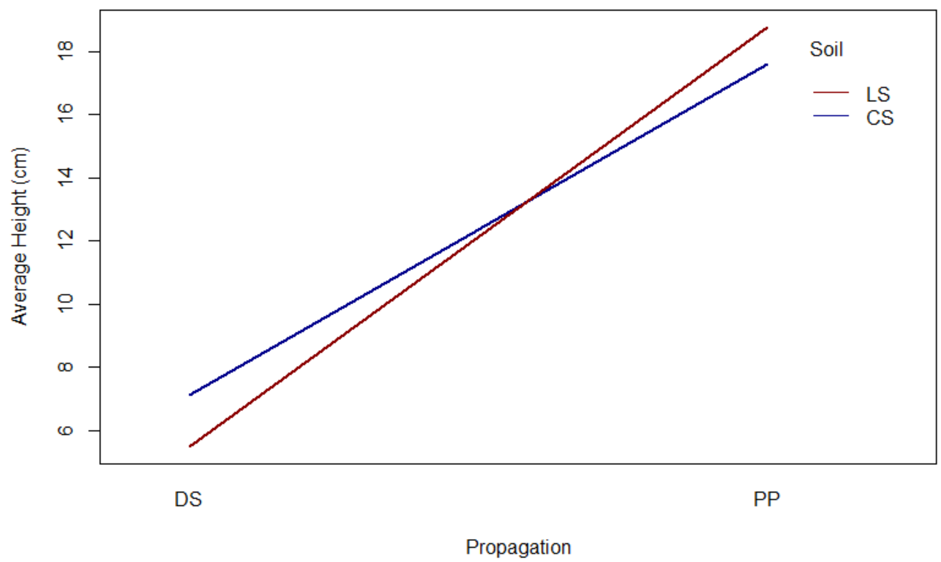
Appendix B. Plot showing the significant three-way interaction occurring between propagation/*Sedum*/soil for estimated biomass on August 17, 2020 (**A**) and September 24, 2020 (B).



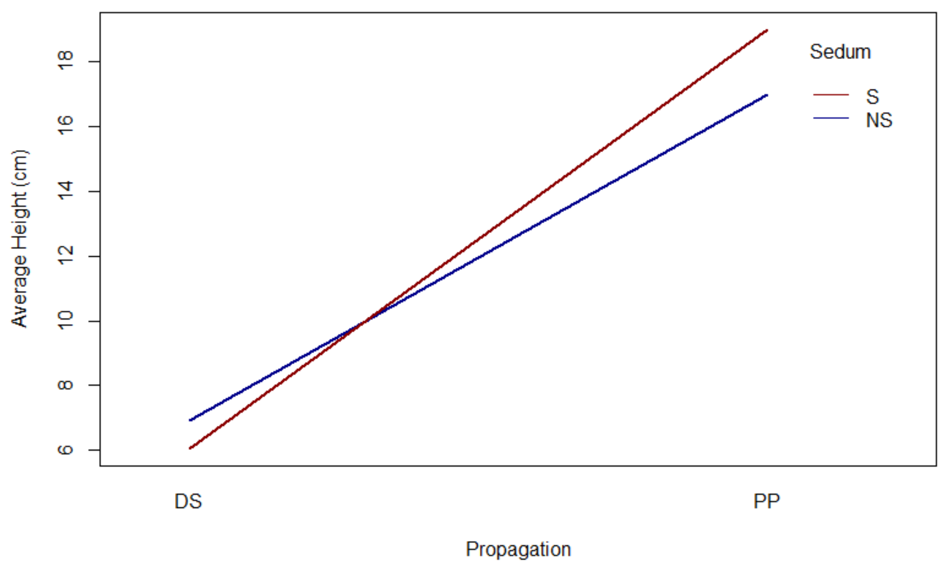
Appendix C. Plot showing the significant two-way interactions for estimated weed biomass occurring between propagation/soil on August 17, 2020.

Heights

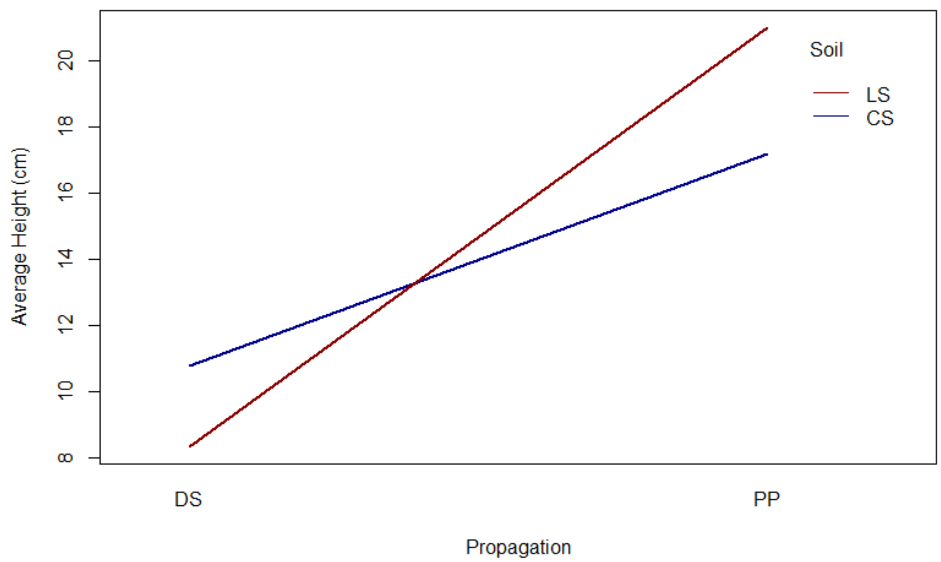
A


Soil
LS
CS
Average Height (cm)
6
8
10
12
14
16
18
DS
PP
Propagation

B


Sedum
S
NS
Average Height (cm)
6
8
10
12
14
16
18
DS
PP
Propagation

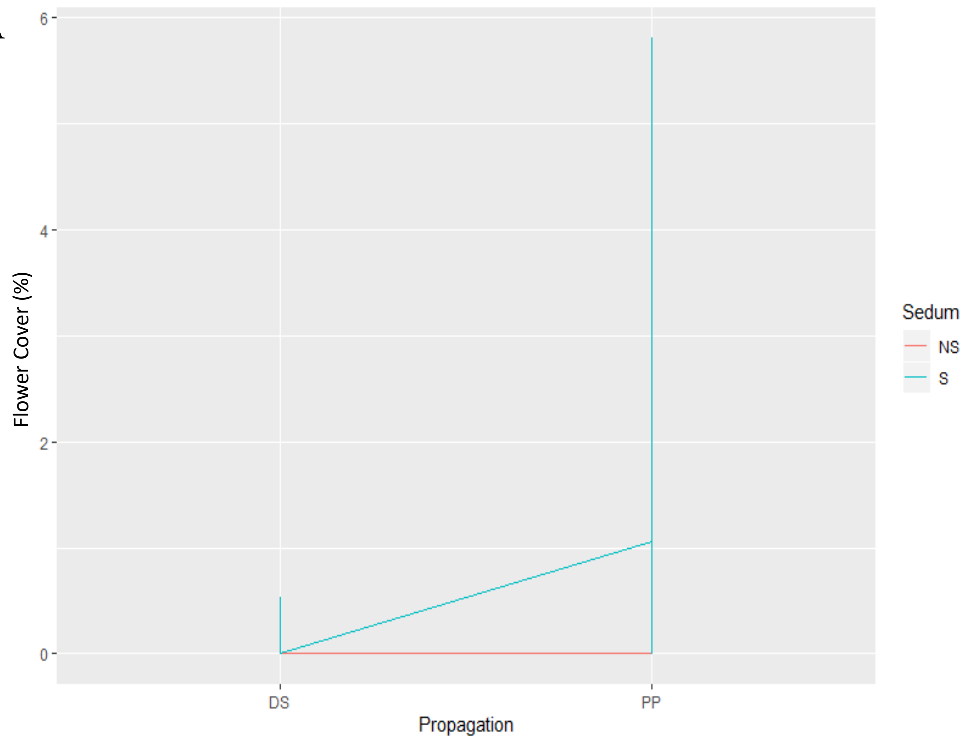
C



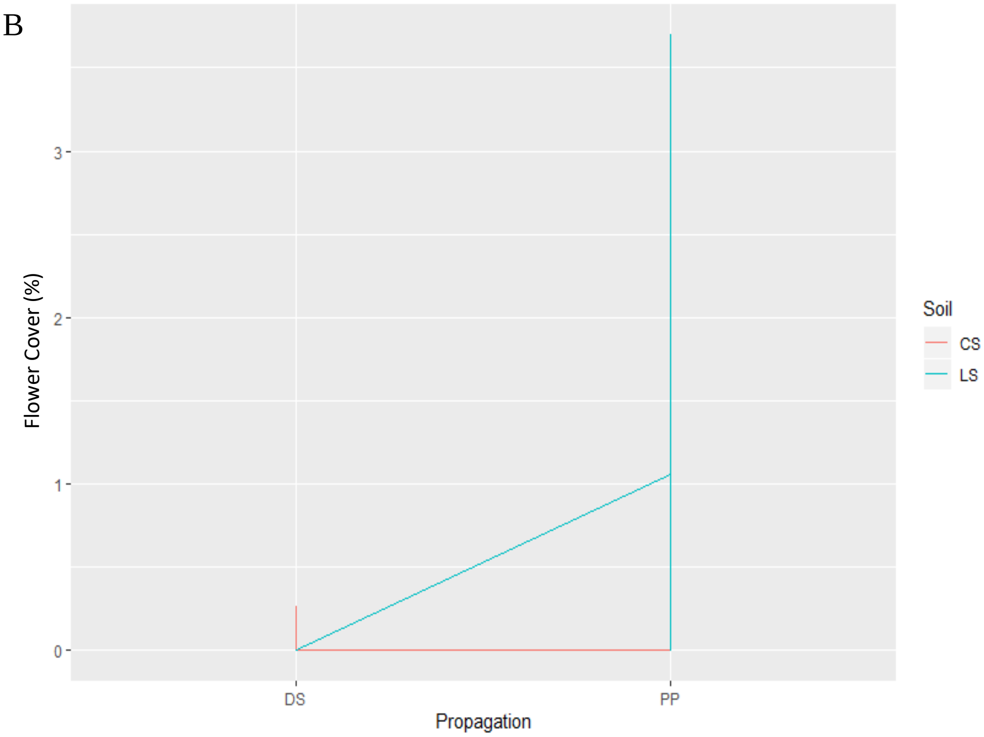
Appendix D. Plots indicating the direction of each interaction between treatments. Interactions occurred between *Sedum*/propagation on August 10, 2020 (B) and soil/propagation on August 10, 2020 (A) and August 27, 2020 (C).

Flower Cover

A

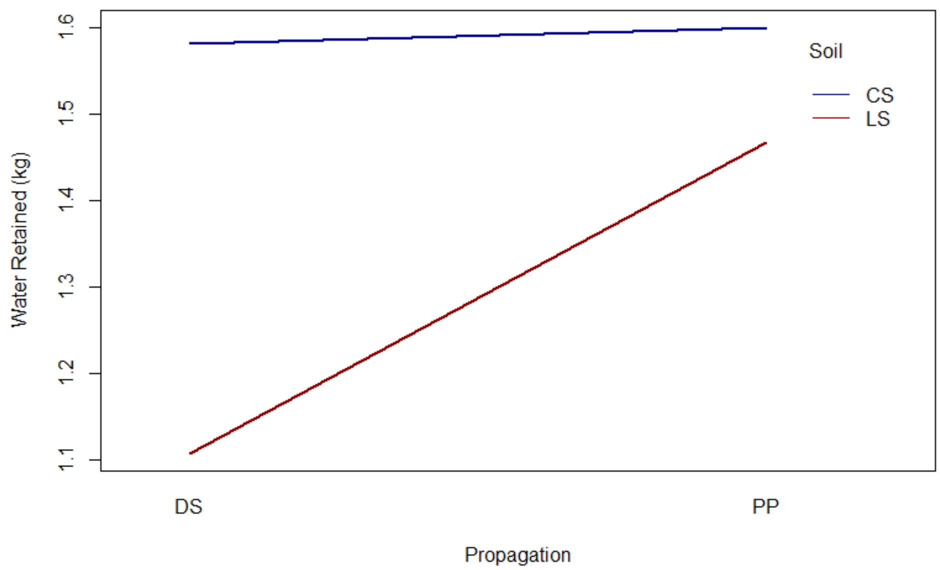


B



Appendix E. Plots indicating the direction of each interaction between treatments. Interactions occurred between *Sedum*/propagation on August 10, 2020 (A) and propagation/soil on August 27, 2020 (B).

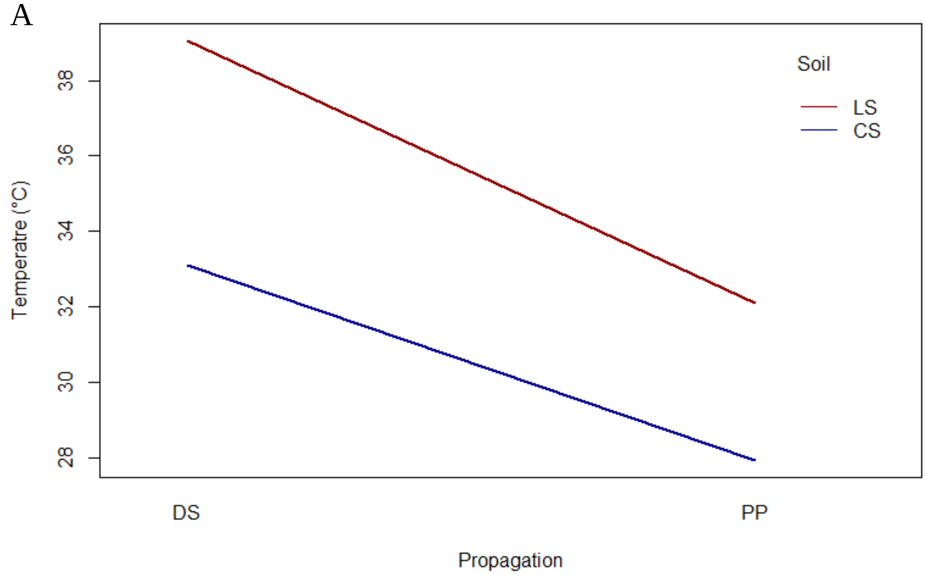
Water Retention



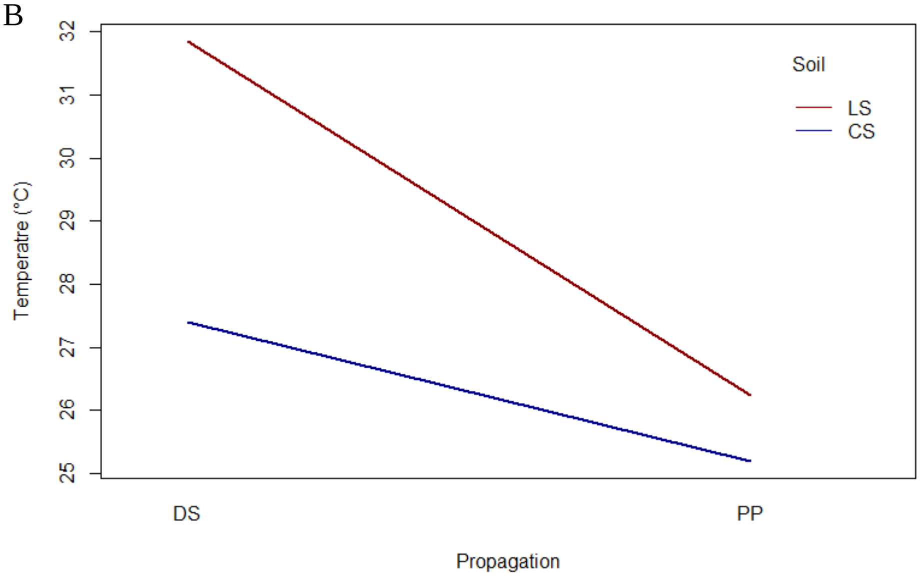
Appendix F. Interaction plot indicating the direction for soil and propagation on July 22, 2020.

Temperature

A



B



Appendix G. Interaction plot indicating the direction for soil and propagation on July 21, 2020 (A) and August 17, 2020 (B).