SUSTAINABLE DESIGN FOR A SUBTROPICAL GREEN ROOF WITH LOCAL, RECYCLABLE SUBSTRATES AND NATIVE PLANT SPECIES

A Senior Scholars Thesis

by

ANGELICA MARIA HUERTA

Submitted to the Office of Undergraduate Research
Texas A&M University
in partial fulfillment of the requirements for the designation as

UNDERGRADUATE RESEARCH SCHOLAR

April 2009

Major: Civil Engineering

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Approved by:

Research Advisor:	Bryan Boulanger
Associate Dean for Undergraduate Research:	Robert C. Webb

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ABSTRACT

Sustainable Design for a Subtropical Green Roof with Local,
Recyclable Substrates and Native Plant Species.
(April 2009)

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As sustainable development becomes the norm, such innovations as the green roof are becoming more commonplace around the world. However, designs tailored for specific climatic regions are still in their infancy. Vegetation and substrate are elements of a green roof that need to be suited for each microclimate and not universalized. Furthermore, sustainable design of a green roof must be based not only on the nature of its benefits, but on its individual components, as well. The use of local and recycled materials needs to be included as a means of minimizing environmental impacts and improving local economies. The goal of this research was to test for vegetation and substrate suitability for a subtropical climate green roof found in East Texas based upon tenets of sustainable design focused on minimizing environmental impact.

Three timber frame plant boxes measured at one square meter were constructed with various substrate depths. Each box contained a different substrate: local topsoil with compost, expanded shale with compost, and recycled crushed concrete with compost. The boxes were further subdivided into four plots with plantings of *Lenophyllum texanum* (coastal stonecrop), *Buchloe dactyloides* (buffalograss), and *Bouteloua gracilis* (blue grama). Each box contained varying substrate depths within the individual plots: 4 inches, 6 inches, and two plots of 8 inches. Results of the study supported successful native plant establishment and the use of local, recycled substrates. These findings give information for sustainable design of green roofs in East Texas and other similar subtropical climates.

DEDICATION

My ambitions and ideas on improving our current state of the environment did not go unnoticed. My family always helped guide me to work toward this passion by testing my commitment most often, and I am ever grateful for the strength of my convictions this has brought. And to my best friend who reignited my dormant passion for the environment and pushed me toward action and a more sustainable lifestyle deserves recognition as well, even if not wanted.

ACKNOWLEDGMENTS

Many individuals were instrumental in my research and graciously took time to assist me. For taking a chance on me, constructing green roof boxes and not even getting mad when I destroyed some of his tools, my ever patient research advisor never lost hope in me and deserves thanks beyond belief. Constructing the green roof boxes proved a challenge and appreciation extends to members of Boulanger’s research team who offered assistance, especially Aditya Bhat. I would also like to extend thanks to all the people who helped with the materials and made my life just a little bit easier: a generous donation from the City of Bryan Compost Facility; always friendly and helpful advice from the folks at Producers Cooperative; and Scott Cronauer for going out of his way to find and crush concrete repeatedly with me. My desire to study green roofs in particular owes its existence to the creation of the class Engineering Projects in Community Service (EPICS) by Dr. Yale Yurttas at our campus. Finally, Mary Ann Jacob and Kevin Grossman are more in tuned with finding their names in the acknowledgments section of books but I owe them huge thanks (and work hours) for being flexible at putting my research over work many times.

NOMENCLATURE

B/CS	Bryan/College Station
cm	Centimeter
CO	Carbon Monoxide
CO_2	Carbon Dioxide
EIO	Economic Input-Output
EIO-LCA	Economic Input-Output Life Cycle Assessment
g	Grams
GWP	Global Warming Potential
lb	Pounds
LCA	Life Cycle Assessment
m	Meters
mt	Metric tons
NOx	Nitrogen Oxides
in	Inches
SO_2	Sulfur Dioxide
TJ	Terajoules
TX	Texas
U.S.	United States

TABLE OF CONTENTS

Page

LIST OF FIGURES

LIST OF TABLES

CHAPTER I

INTRODUCTION

Green or vegetative roofs have become an all-in-one technology, or best management practice, to combat flawed urban design related to storm water, heat island effect, air pollution, wildlife habitat, roof longevity, and noise pollution (Getter and Rowe, 2006). Germany pioneered the modern green roof to be extensive (little maintenance, irrigation, and inputs), with *sedum* as the chief form of vegetation in low organic, mineral based substrates. However, the recent transition of this technology to the U.S. has initiated research for more appropriate designs. Designing green roofs needs to take into account specific locations with their microclimates and respected vegetation; what has worked in Germany will most likely not work in all of the U.S. Thus far most research in this country has been made in the East and Midwest (DeNardo et al., 2005; VanWoert et al., 2005; Getter and Rowe, 2008; Hathaway et al., 2008; Sutton, 2008). Simmons and Gardiner are conducting research within Texas where a subtropical climate exists (Simmons et al., 2008). However, in Texas alone there are five different microclimates with subtropical being one (Larkin and Bomar, 1983). The above studies have served to confirm general characteristics of green roofs – storm water retention and quality, substrates, plant species, and energy conservation – with respect to the U.S. Subsequently the question now arises whether green roofs can be deemed sustainable if

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This thesis follows the style of Ecological Engineering.

they are being standardized and their components manufactured on a large scale. Many of the studies conducted in the U.S. have utilized commercial materials, some recycled, from leading green roof manufacturers. The technology is being marketed as a form of sustainable development, but, sustainable design initiates from certain criteria that is implemented, whereas modern green roofs are an established technology that validates its sustainability on how many benefits it can create. This then warrants an evaluation of their design.

Sustainable design

Place-based design incorporates green and sustainable principles with local energy, materials, and labor for a specific site (Williams, 2007). It follows the ecological model of working with what you got. A similar approach is related to sustainable autonomous development (Kellogg and Pettigrew, 2008) where affordability, salvaged/and or local materials, simplicity, and decentralization form the main design criteria. Kellogg and Pettigrew recognize that autonomous design "reduces virgin supply demand, slows consumption and minimizes expense and keeps production locally." In a more formal context, several tenets of roofing sustainability have been identified by the International Council for Research and Innovation in Building Construction (CIB, 2001). The three main tenets are: minimizing the burden on the environment, conserving energy, and increasing roof lifespan. Green roofs have been shown to conserve energy and improve roof longevity (Getter and Rowe, 2006). This study provides a closer examination at the sub-tenets of minimizing the burden on the environment. There are seven sub-tenets with one explicitly suggesting the use of green roofs. Five of the remaining deal in some way with minimizing waste and resource extraction by reusing or recycling materials, and the last focus is on local resources. Thus these sub-tenets should drive design criteria of green roofs if they are to be labeled sustainable.

Current design and research

So far attempts at green roof sustainability have come from using native species (limited regions though), recycled manufactured materials, and reused organic materials (sometimes local) such as compost and fertilizer. Continued research with native plant species is needed with additional local and/or recycled materials. Such materials extend to using recycled construction and demolition wastes for the drainage layer, substrate, and green roof frame. Combine this with local resource bases and green roof materials have the potential to come from neighborhood nurseries, construction companies, salvage yards, and waste receptacles. New markets have been created by green roofs for nurseries and landscape contractors (Getter and Rowe, 2006), the same can apply for construction companies specializing in recycled construction materials. Likewise, utilizing recycled materials can help construction companies and clients offset the high initial capital costs associated with present green technology.

Future design and research

Therefore an attempt is made to study an autonomous green roof to further support traditional elements but coupled with the use of salvaged materials. This research will evaluate the performance of local and recyclable growth substrates and native plants based on place-based design which can then be incorporated into green roof design throughout our region. Two hypotheses will be explored:

1) Local, recycled substrates used as plant growth media have lower environmental impact than commercial synthetic and/or plain local growth substrates.

2) Native plants will have successful establishment, growth and temperature resistance, for a subtropical climate green roof.

Performance indicators will be temperature gradients in the substrates, substrate pH, and vegetation growth. This study hopes to reinforce areas already researched for green roofs: deeper substrate increases plant survival (Boivin et al., 2001; VanWoert et al., 2005; Durhman et al., 2007; Dunnett et al., 2008; Getter and Rowe, 2008) and native plant hardiness ((Monterusso et al., 2005; Simmons et al., 2008; Sutton, 2008)).

While a green roof’s label as sustainable relies on its qualities, it cannot however produce these without its individual components being founded upon the same principles. To be sustainable, design must work with local energies, materials, and labor, or model nature. Several traditional elements of green roofs will be studied with this in mind. The dynamics of the system will demonstrate the feasibility of creating more sustainable green roofs and provide a starting point for further discussion on autonomous sustainable design within the current technology market.

CHAPTER II

METHODS

Model development

In keeping with place-based design, autonomy, and tenets of sustainability as discussed earlier, the construction and energy inputs for the green roof system were explored. Additionally, metrics for sustainability were established to support these ideas. The metrics were created for an East Texas region; which is one of the many climatic and hardiness zones of the U.S. (Fig. 1). Many articles, books, and standards discuss several characteristics of successful green roof systems. These systems should: be structurally sound due to live and dead loads; have adequate and proper drainage; waterproofing to prevent leaking; a root barrier layer to prevent penetration; a drainage and/or retention layer; filter fabric; additional protection along penetrations; fire and wind safety. All of these characteristics were addressed with more emphasis on others. More importantly, to validate the hypotheses several field assessments were conducted to offer new data and comparison from previous studies in the field of green roof technology.

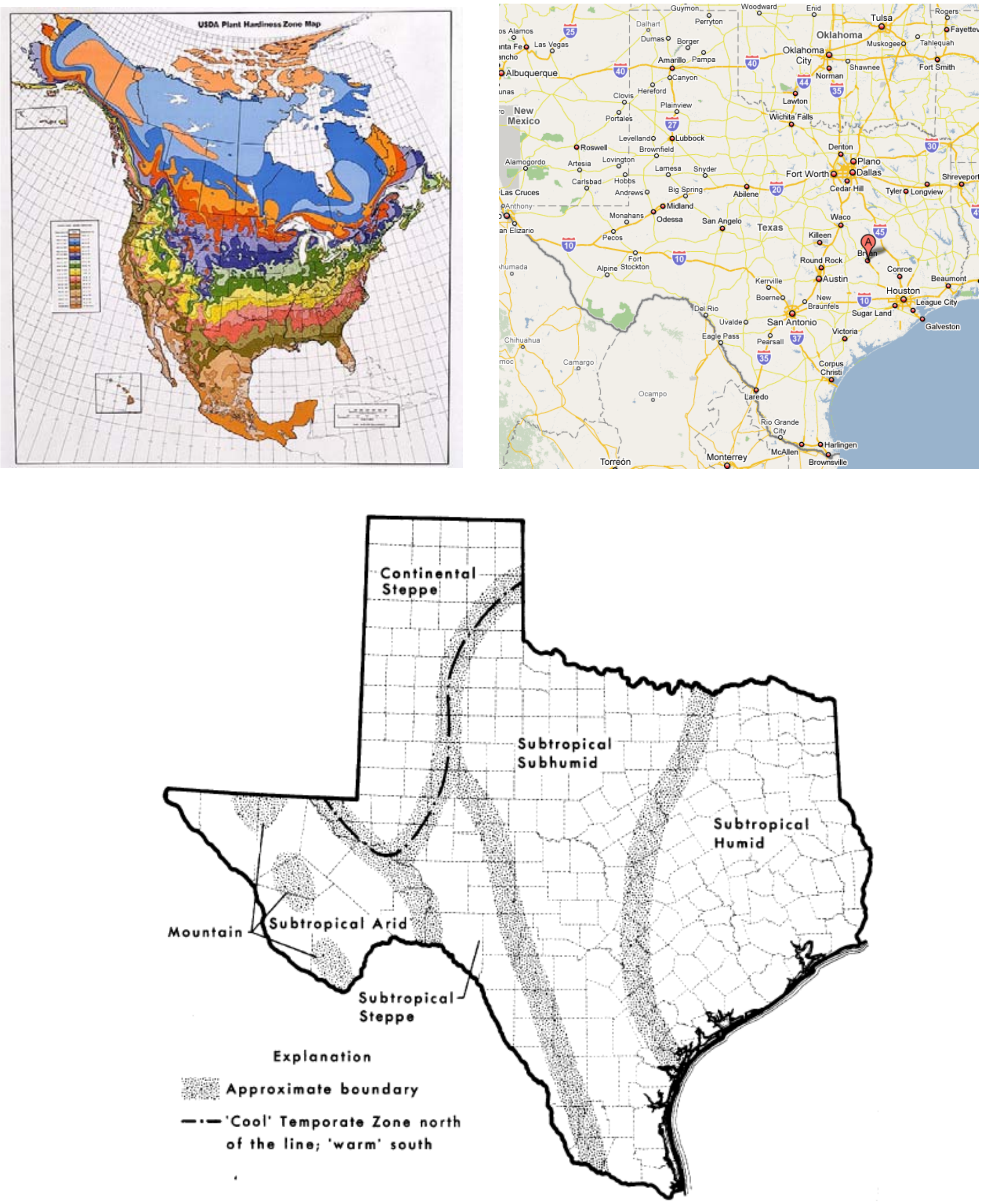


Fig. 1 – Climate differentiations for the U.S. and Texas. Clockwise from top left: USDA plant hardiness zones, location of Bryan/College Station, and climatic zones of TX.

Metric for sustainability

The metric followed four main ideas: local, native, recycled, and reused.

Local

Purchasing and utilizing local materials and services helps promotes the local economy. Small businesses and community members benefit from this association which in turns ensures a healthy and safe community atmosphere. There is also a higher probability that the materials are of local or regional production; transportation costs and its impact to the environment (fuel, packaging) often decrease because of this.

Native

Planting native species on green roofs promotes local biodiversity and ensures the sustainability of a region's flora and fauna. Likewise, native species are more adapted to a region's extreme climatic conditions compared to nonnative species, and have a better chance of surviving atop a roof.

Recycled

By using recycling goods this helps to promote businesses in this sector and divert waste from landfills. Recycling serves to keep a material in the production process and eliminates the need for virgin extracted resources. Ideally, such goods should be less expensive as their production values are less.

Reused

Reusing materials diverts waste into landfills momentarily and offers economic benefits for such businesses as construction companies to resell their waste. Instead of paying to dispose of demolition waste such as concrete, it can be bought and given a second life. Even if only temporarily, reusing minimizes the environmental and ecological costs that come with landfills – land transformation, leachate, habitat destruction, etc. Moreover, reusing materials involves creative thinking, a crucial element of sustainability and self-evolution.

Design loads

One of the crucial factors affecting the type of system and its feasibility is its design loads. An extensive green roof system is typically more lightweight than the intensive green roof. Its weight due to the individual components, particularly water saturation and vegetation types are on the lighter side. In this study, little attention was given to loads as this was not the main concern, however, they were considered. For the construction of the boxes, materials that could lighten the dead load were investigated. Extruded polystyrene for insulation and ½ inch thick plywood were used. In designing the drainage layer a media mixture was selected that could offer a wide range of coarseness and distributed load. The stone substrates were also chosen to provide for quick draining properties to lessen time of saturation.

Drainage

A drainage layer is a required element in such a system whereas water retention, reservoir, or aeration layers are optional; or they can be integrated into one to form the drainage layer. Ideally the drainage layer serves to collect and evenly redistribute water. It should act as a reservoir for roots to tap into, adequately and efficiently distribute water, especially storm water. Furthermore it acts as a stable support course for the fabric.

Protection

Several protective measures can be incorporated into a green roof. In this study redundancy with the waterproofing and filter fabric served to prevent future root damage. Also, the filter fabric provided protection from any tears from the rocks in the drainage layer to the waterproofing membrane.

Natural elements

Wind and fire hazards also need to be considered. Because of the amount of vegetation used, a fire hazard was given a low priority for this study. Likewise, the site is shielded from wind on the west side and is only one-story above ground (Fig. 2); the possibility of wind picking up materials was low.

Fig. 2 – Site location of plots. The green roof boxes are located on a one-story patio with its own drainage problem.

Construction

The green roof plots were designed to be built of everyday materials available to any homeowner. Two lumber frames of 2 x 4's at 1 m^2 were screwed together atop a plywood base also measuring 1 m^2. Lumber supports were added within the box and then additional 2 x 4's were screwed in to divide the box into four plots. Three boxes were built as such.

Fig. 3 – Construction of green roof plots. Clockwise from top left: frame, insulation layers, insulation and waterproofing and drainage layer.

Once the frame was completed the individual layers of the green roof system were built up (Figs. 3 & 4). First a layer of polystyrene insulation was added followed by the waterproofing membrane. A simple pond liner was used and covered the entire inside of the plots; at joints and corners the membrane was reinforced with extra lining. The waterproofing also served as a potential root barrier. A filter fabric was then laid to provide further protection from root damage, allow capillary action, and filter out silt from the succeeding layers. A 2 inch drainage layer of mixed grade rocks was then evenly distributed atop this (Table 3) and then topped with another layer of fabric. This particular fabric spanned the entire height of the plots as to be accessible at the vegetation level. Finally, varying levels of substrate (Table 1) were added to the plots.

Each box had plots of substrate depths of 4 inches, 6 inches, and two of 8 inches (Figs. 5 & 6).

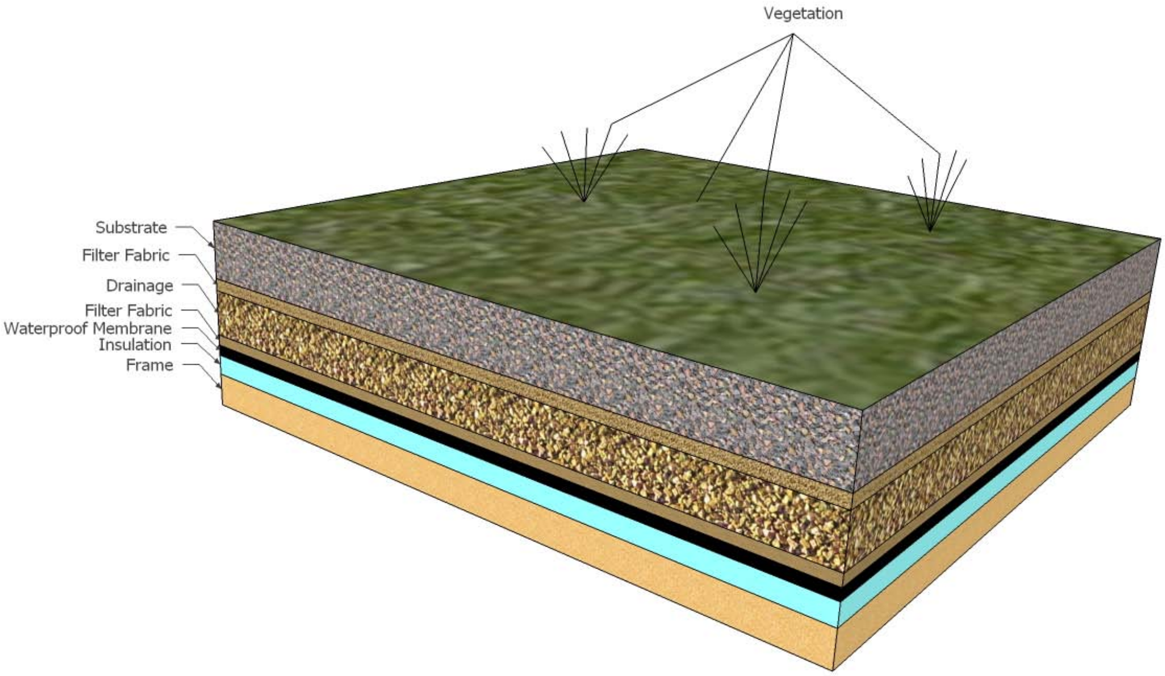
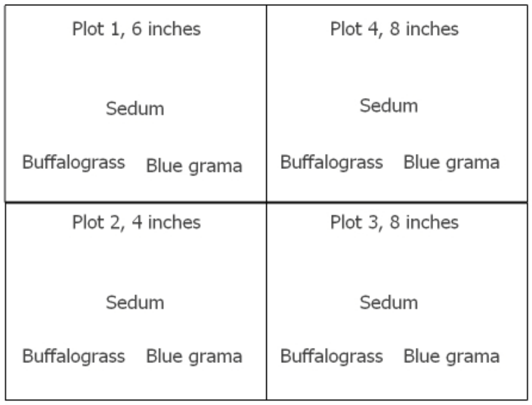


Fig. 4 – Green roof layers.



Plot 1, 6 inches Sedum Buffalograss Blue grama	Plot 4, 8 inches Sedum Buffalograss Blue grama
Plot 2, 4 inches Sedum Buffalograss Blue grama	Plot 3, 8 inches Sedum Buffalograss Blue grama

Fig. 5 – Plot setup. Each box was setup as represented but with the type of substrate varying.

Table 1 - Substrate composition

Box	Plot	Percent Volume	Weight (lbs)
1	1	80% expanded shale[a], 20% compost[b]	43
	2	80% expanded shale[a], 20% compost[b]	56
	3	80% expanded shale[a], 20% compost[b]	60
	4	80% expanded shale[a], 20% compost[b]	62
2	1	80% crushed concrete[c], 20% compost[b]	55
	2	80% crushed concrete[c], 20% compost[b]	76
	3	80% crushed concrete[c], 20% compost[b]	87
	4	80% crushed concrete[c], 20% compost[b]	89
3	1	80% local topsoil[d], 20% compost[b]	29
	2	80% local topsoil[d], 20% compost[b]	40
	3	80% local topsoil[d], 20% compost[b]	64
	4	80% local topsoil[d], 20% compost[b]	60

[a] Lady Bug Natural Brand Expanded Shale; mined in North Texas.

[b] City of Bryan, Texas VitaSoil compost - derived from green waste and municipal bio-solids

[c] Donated concrete department, source unknown; crushed on-site.

[d] City of Bryan Neal Park Community Garden topsoil

Each box then received three plantings, one of a coastal stonecrop plug, one of buffalograss seeds, and the other of blue grama seeds (Table 2). (The coastal stonecrop is equivalent to a *sedum* and will thus be referred to as such from now on.) A watering of 340 mL was then applied for a modest soaking.

Table 2 – Grass seed distribution for each plot. The seeds were spread out evenly within a defined area of each plot.

	Buchloe dactyloides (buffalograss)	*Bouteloua gracilis* (blue grama)
Each individual plot contained:	1.6 g	0.9 g

Fig. 6 –Completed green roof plots. Clockwise from top left: completed box of shale with compost; completed box of recycled concrete and compost; and all completed boxes with the box of topsoil and compost in foreground.

Materials

As noted before many of the materials came from local and regional hardware stores (The Home Depot and Lowe’s) and nurseries (Producer’s Cooperative, Yucca Do Nursery, and Native American Seed). Purchasing from the leading green roof manufacturers was not viewed as sustainable considering: the transportation costs, availability to the average homeowner, and the possibility of synthetic chemicals used in the production of specific green roof technologies. Unfortunately, concession was made in using materials such as PVC waterproofing, and wood for the box.

Some of the materials were recycled and scavenged, particularly the drainage and substrate layers. In the best scenario a project's materials come from onsite as did the entire drainage layer which was scavenged out of an engineering dumpster behind the site. The crushed concrete was acquired with the help of the engineering concrete lab. The lab's supervisor was given waste concrete cylinders that had been weathering outside with no intended use. They were donated and personally crushed with an electric stone crusher, also donated temporarily. Each box also contained compost from a sister city's recycling compost facility; the compost is made of green waste (grass clippings, tree trimmings and leaves) and bio-solids.

Table 3 - Drainage layer aggregate composition

Box	Aggregate	Description	Weight (lbs)	Total Weight (lbs)
1	A	slate/gravel gravel	6	6
	B	multicolored (white/pink/gray) coarse gravel	13	19
	C	multicolored, fine coarse grade rock	14	33
	D	white fine gravel	8	41
	E	Yellow, mixed coarse/fine stone	16	57
2	A	slate/gravel gravel	6	6
	B	multicolored (white/pink/gray) coarse gravel	13	19
	C	multicolored, fine coarse grade rock	14	33
	D	white fine gravel	8	41
	E	Yellow, mixed coarse/fine stone	16	57
3	A	slate/gravel gravel	6	6
	B	multicolored (white/pink/gray) coarse gravel	13	19
	C	multicolored, fine coarse grade rock	14	33
	D	white fine gravel	8	41
	E	Yellow, mixed coarse/fine stone	6[a]	47

[a] An oversight in the distribution ended up with only 6 lbs of aggregate E being available for the topsoil box. This was left as is because the aggregates were salvaged and supply limited.

Selecting whom to purchase the vegetation was assisted by the Lady Bird Johnson Wildflower Center. During a trip to view the Center’s own green roof research, it was found that many of their native species come from Native American Seed, which the *Buchloe dactyloides* (buffalograss), and *Bouteloua gracilis* (blue grama) were purchased. The *Lenophyllum texanum* (Coastal stonecrop) was ordered from Yucca Do Nursery, as recommended again by the Center, for its proximity to College Station.

Field evaluations

One of the main performance indicators for this study was to monitor plant growth and survival especially during its germination over the winter. This was carried out with ocular observations by photographs and measuring vegetation dimensions. Additionally, the pH and soil temperatures were measured periodically as means of showing pH changes and ambient air temperature differences.

Life cycle assessment

A selective life cycle assessment (LCA) was conducted using an Economic Input-Output Life Cycle Assessment (EIO-LCA) online tool (Carnegie Mellon, 2009). LCA investigates the environmental burden caused by a product, material or process over its lifetime. This involves quantifying its material and energy flows through resource extraction, production/manufacturing, use, and end-of-life activity. This inventory offers a comparison of what areas of a product contributes the most to environmental degradation and where design improvement can occur. In particular, an EIO-LCA incorporates the monetary, direct, and indirect transactions between industry sectors in their relationship to the product, material, or process, but with the addition of an environmental sector. Thus exchanges can be related to the impacts that occur to the environment from all interrelated industries. The scope of the EIO-LCA was to compare the environmental impacts of the green roof substrates and the main component of a conventional gravel ballast roof – gravel. The topsoil was not included in this LCA as it would have a significantly lower impact versus the other materials as it only incurred local transportation costs.

CHAPTER III

RESULTS

After initial plant establishment field evaluations were conducted to measure substrate pH and temperature, and dimensional growth. Ocular observations provided the majority of field evaluations. A simple and selective life cycle assessment compared the main components of the green roofs and a traditional gravel ballast roof.

A month into the study substrate pH and temperatures were measured. Four days, a week after planting (12/28) and three consecutive days in late January have data. Recording ended due to the pH meter breaking. Figure 7 shows the differences in the ambient temperature to the substrate temperatures. The first data point, 12/28, showed temperature differences in the boxes between -0.1 to +3.2 degrees. January 28 had temperatures differentiate from ambient temperature by -7.5 to +11.6 degrees. A difference of -3.2 to -.3 degrees and -7.32 to -2.8 degrees were recorded for January 29 and 30, respectively. Factors influencing temperature differences were time of day for measurements. Not all days were measured at the same time, for example the greater variability for January 28 is because it was measured the earliest in the day (noon) and the day in particularly was significantly colder (6.1°C or 43°F). Daily ambient temperature averages also varied with the substrate temperature (Fig. 8).

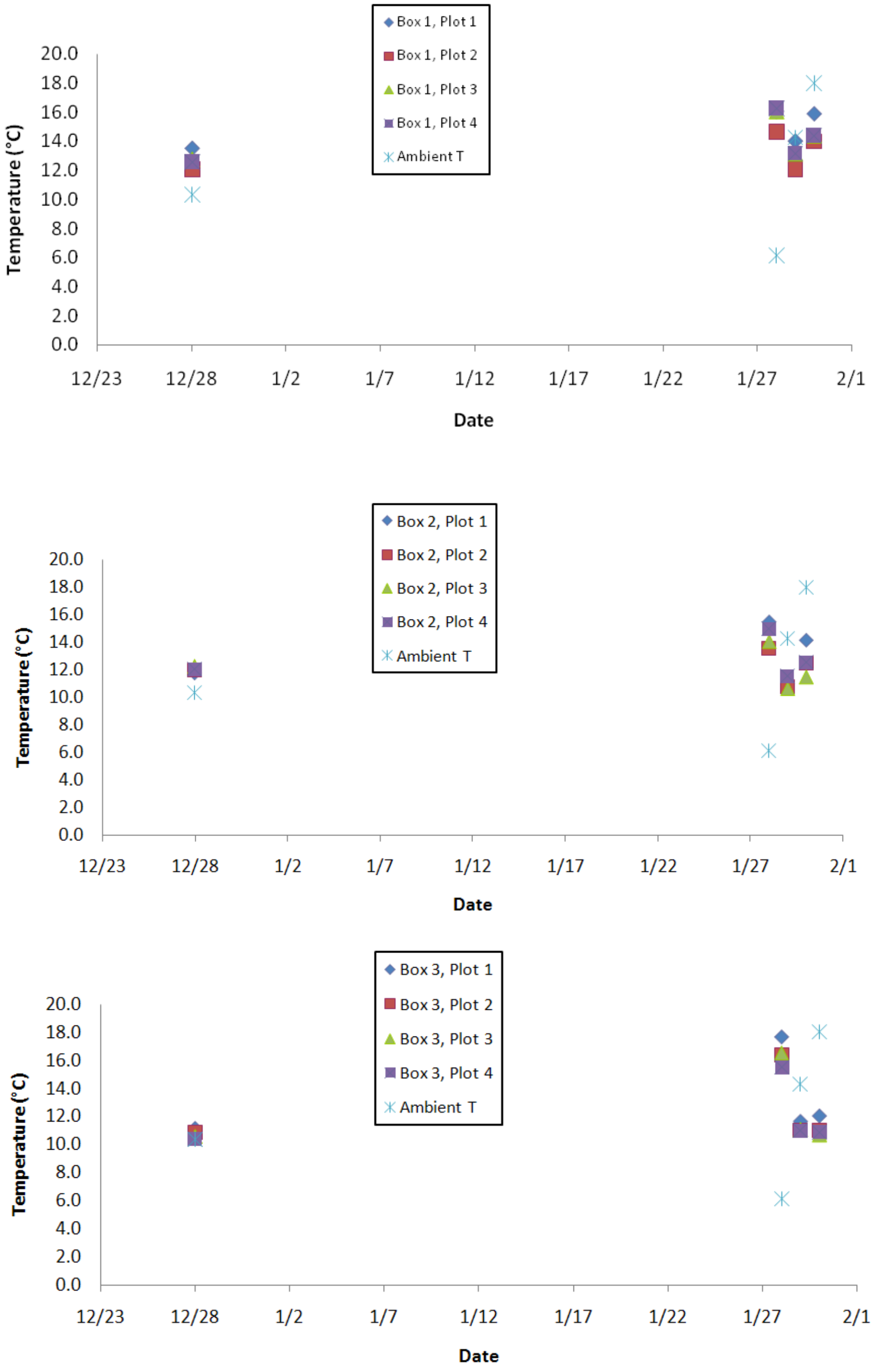


Fig. 7 – Temperature measurements of substrate for each plot versus ambient temperature.

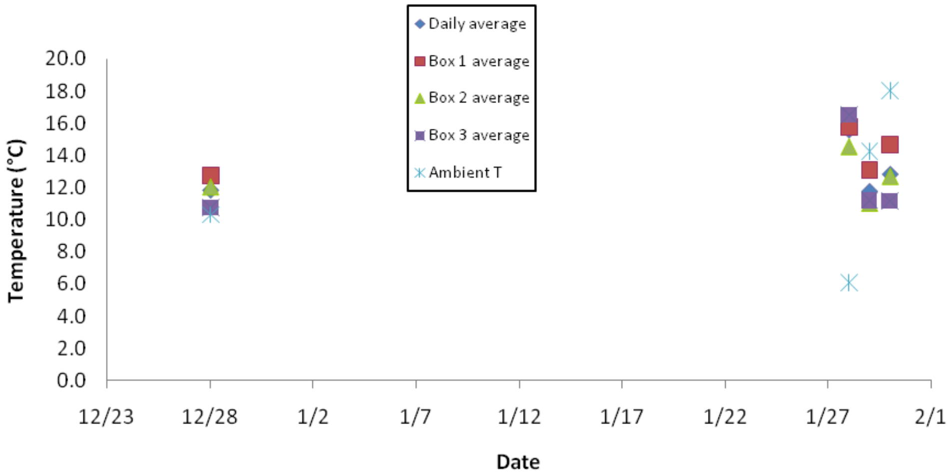


Fig. 8– Box temperature averages for each substrate versus ambient temperature.

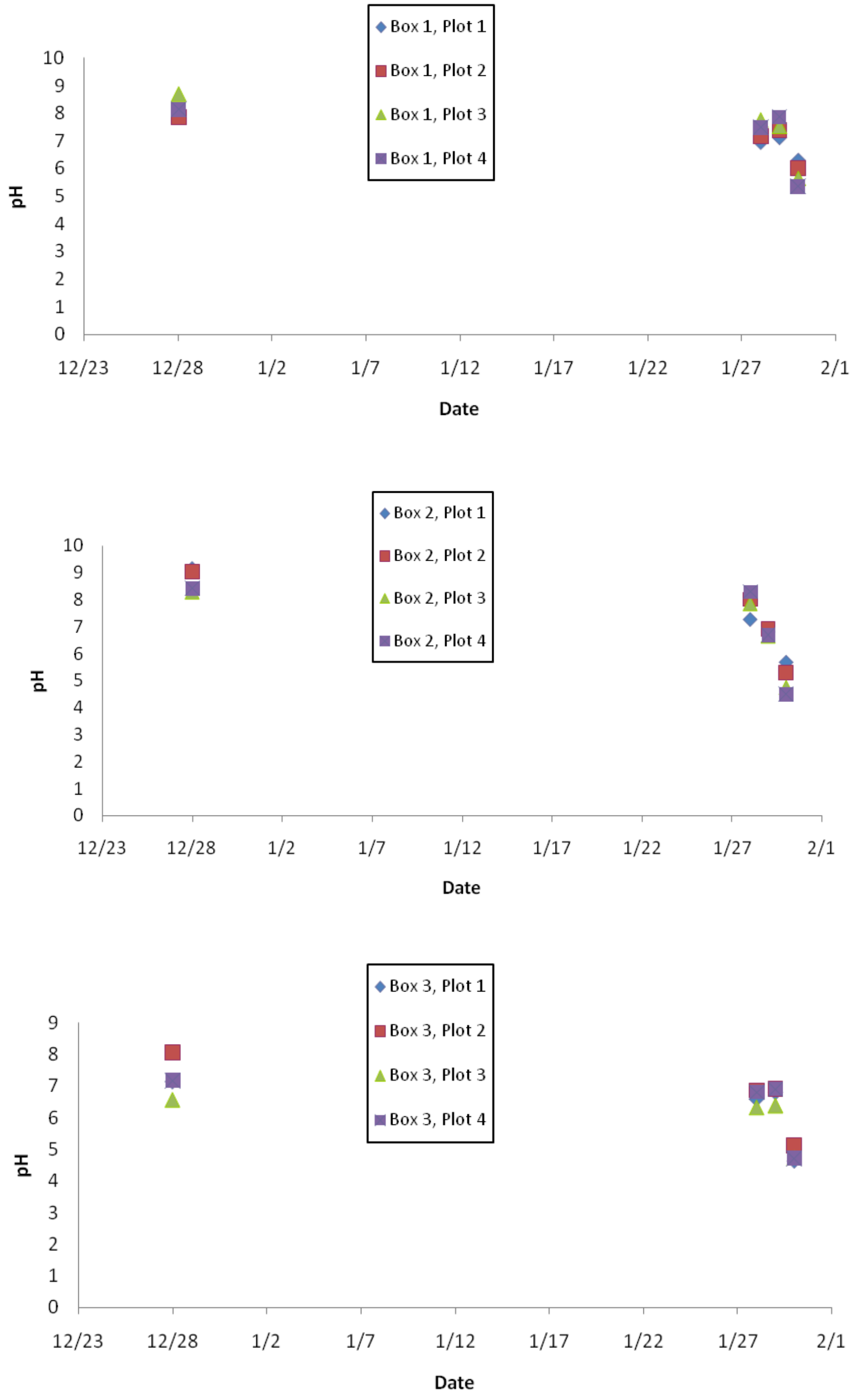


Fig. 9 – Substrate pH measurements for each plot.

The pH in all boxes gained in acidity over time with the greater changes in the shale and concrete substrates (Fig. 9). The concrete started off with an average pH of 8.73 and declined to pH 7.86 in a month. Likewise, shale exhibited an average pH of 8.19 and pH 7.34 one month later; and the topsoil substrate had an average pH of 7.25 and a month later pH 6.66.

Measurements of vegetation dimensions were taken three months after planting (Tables 4-7), and several ocular observations show roughly two week intervals of vegetation growth (Appendix). All *sedum* were able to withstand the winter conditions. Visually they have gone from purple and brown leaves to full, vibrant green leaves with many of them losing their flower branches because of wind. Two plots (Box 1, Plot 1and Box 2, Plot 2) had fallen leaves regenerate into new *sedum* plants. Buffalograss was the more successful of the grasses, with the most growth in the 6 in plots followed by the 4 in (Table 7). The blue grama was the first grass to sprout but died off and has returned to the concrete and shale boxes slowly. In the topsoil the 4 inch plot is the only one that has blue grama growing. Furthermore, the blue grama is less dense in all plots where found compared to the buffalograss. The buffalograss is found in all plots throughout all boxes in dense tufts. Finally, a month into the study insects began inhabiting the plots. Currently, there are spiders, aphids and ants.

Table 4 - Vegetation growth Dimensions[a] taken on March 16, 2009

Box	Plot	Tallest buffalograss blade (cm)	Tallest blue grama blade (cm)	*Sedum*: width A (cm)	*Sedum*: width B (cm)
1	1	7.9375	5.7150	8.255	6.6675
	2	8.2550	5.3975	7.9375	8.89
	3	7.3025	3.8100	6.0325	6.985
	4	6.9850	3.1750	6.0325	7.46125
2	1	6.3500	5.0800	7.3025	7.9375
	2	5.7150	5.7150	9.2075	7.62
	3	6.6675	5.0800	8.255	9.525
	4	6.0325	3.1750	7.3025	8.89
3	A	7.6200		5.715	12.54125
	B	3.1750		9.525	10.795
	C	4.1275		6.35	6.6675
	D	3.8100		11.1125	11.43

[a] Blank spaces mean no vegetation present.

Table 5 - Vegetation growth dimensions[a] taken on March 30, 2009

Box	Plot	Tallest buffalograss blade (cm)	Tallest blue grama blade (cm)	*Sedum*: width A (cm)	*Sedum*: width B (cm)	New *sedum*[b]: width A (cm)	New *sedum*[b]: width B (cm)
1	1	11.1125	7.6200	9.8425	8.255	0.9375	1.125
	2	13.0175	7.6200	8.255	10.00125		
	3	10.7950	6.9850	6.985	8.89		
	4	11.5888	4.6038	7.9375	8.255		
2	1	9.5250	6.3500	9.8425	9.525		
	2	10.1600	6.6675	10.16	8.5725	0.625	0.625
	3	8.8900	7.6200	8.89	11.1125		
	4	8.5725	6.9850	7.62	9.8425		
3	A	15.0813		17.4625	15.24		
	B	6.9850	0.6350	11.43	14.605		
	C	6.3500		9.525	10.00125		
	D	8.5725		15.08125	14.9225		

[a] Blank spaces mean no vegetation present.

[b] Represents leaves from initial *sedum* that have propagated into new separate plants.

Table 6 - Differences in vegetation growth dimensions[ab]

Box	Plot	Tallest buffalograss blade (cm)	Tallest blue grama blade (cm)	*Sedum*: width A (cm)	*Sedum*: width B (cm)	New *sedum*[b]: width A (cm)	New *sedum*[b]: width B (cm)
1	1	3.1750	1.9050	1.5875	1.5875	0.9375	0.9375
	2	4.7625	2.2225	0.3175	1.11125		
	3	3.4925	3.1750	0.9525	1.905		
	4	4.6038	1.4288	1.905	0.79375		
2	1	3.1750	1.2700	2.54	1.5875		
	2	4.4450	0.9525	0.9525	0.9525	0.625	0.625
	3	2.2225	2.5400	0.635	1.5875		
	4	2.5400	3.8100	0.3175	0.9525		
3	A	7.4613		11.7475	2.69875		
	B	3.8100	0.6350	1.905	3.81		
	C	2.2225		3.175	3.33375		
	D	4.7625		3.96875	3.4925		

[a] Blank spaces mean no vegetation present.

[b] Differences were all positive signifying growth.

[c] Represents leaves from initial *sedum* that have propagated into new separate plants.

Table 7 - Increase in grass volume as of 4/9/2009[ab]

Box	Plot	Buffalograss (cm^3)	Blue grama (cm^3)
1	1	563.31	331.84
	2	573.55	122.90
	3	344.13	39.94
	4	322.62	49.16
2	1	107.54	153.63
	2	71.69	32.26
	3	89.62	46.09
	4	131.10	16.39
3	A	307.26	
	B	18.44	0.03
	C	32.77	
	D	81.94	

[a] Blank spaces mean no vegetation present.

[b] Measurements were estimates to the nearest 1/4 in, converted to cm and then represented as a whole number.

EIO-LCA involved a selective inventory of several indicators: Total Economic Effect, Value Added, SO_2, NOx, CO, GWP, CO_2, Total Energy, and Total Toxic Releases/Transfers. These indicators were applied over three sectors representing the crushed concrete (Table 8), expanded shale (Table 9), and gravel for a gravel ballast roof (Table 10). The sector chosen for concrete contained a suitable subset, “wrecking and demolition contractors.” Whereas the shale and gravel, which were classified the same, were categorized under mining. The indicators were selected based on their magnitudes in order to highlight the more significant environmental contributions. All values are based on an input of $1 million for the sector. For example, for every $1 million of

“Other maintenance and repair construction,” of which concrete is included, is produced, \$1.19 million in total economic effects occurs. From the tables it can be seen that this total economic effect is higher compared to the shale and gravel, \$1.04 million. The total economic effect represents the amount of money transferred throughout industries needed to produce the material. Additionally, the value the sector creates, \$6.36 million is considerably higher than the \$0.611 million for the other materials. These values signal the economic importance of the industry. Of the conventional air pollutants, the most emitted was the 1.27 mt of NOx by concrete compared to 0.164 mt for shale and gravel. The GWP or Global Warming Potential is greater for the shale and gravel, 569 $MTCO_2E$, versus the concrete, 365 $MTCO_2E$, with all of the emissions coming from CO_2. The total energy required by the sectors is also greater for the shale and gravel, 10.4 TJ, compared to the concrete at 5.46 TJ. Finally, the amount of total toxic releases and transactions is greater for the concrete, 1.31 kg versus 0.002 kg. Toxic releases are characterized by the amount of toxic substances released into the environment by point and non-point air, water, land, and underground movement. Transactions are toxic substances released into publicly owned treatment facilities such as waste water treatment plants via sewers and drains. Also within transactions are offsite transfers, which include disposal, recycling and treatment, and energy recovery.

Another interpretation of the EIO-LCA is to put everything in terms of \$1 versus \$1 million. For example, for every \$1 that goes into “Other maintenance and repair construction,” it creates \$6.36 in value added.

Table 8 - Selective life cycle inventory of a crushed concrete based substrate for a green roof[a]

Material: Sector	Total Economic Effect ($mill)	Value Added ($mill)	SO_2 (mt)	NOx (mt)	CO (mt)	GWP ($MTCO_2E$)[b]	CO_2 ($MTCO_2E$)[b]	Total Energy (TJ)	Total Toxic Rel/Trans[c] (kg)
Crushed Concrete: Other maintenance and repair construction	1.19	6.36	0	1.27	0.737	365	365	5.46	1.31

[a] Values based on $1 million of input

[b] Metric tons of CO_2 equivalent

[c] Total air (point and non-point), water, land, and underground toxic releases; plus total toxic transactions into publicly owned treatment facilities and offsite transactions.

Table 9 - Selective life cycle inventory of an expanded shale based substrate for a green roof[a]

Material: Sector	Total Economic Effect ($mill)	Value Added ($mill)	SO_2 (mt)	NOx (mt)	CO (mt)	GWP ($MTCO_2E$)[b]	CO_2 ($MTCO_2E$)[b]	Total Energy (TJ)	Total Toxic Rel/Trans[c] (kg)
Expanded Shale: Sand, gravel, clay, and refractory mining	1.04	0.611	0.15	0.164	0.233	569	569	10.4	0.002

[a] Values based on $1 million of input

[b] Metric tons of CO_2 equivalent

[c] Total air (point and non-point), water, land, and underground toxic releases; plus total toxic transactions into publicly owned treatment facilities and offsite transactions.

Table 10 - Selective life cycle inventory of the gravel for a gravel ballast roof[a]

Material: Sector	Total Economic Effect (\$mill)	Value Added (\$mill)	SO_2 (mt)	NOx (mt)	CO (mt)	GWP ($MTCO_2E$)[b]	CO_2 ($MTCO_2E$)[b]	Total Energy (TJ)	Total Toxic Rel/Trans[c] (kg)
Gravel Ballast: Sand, gravel, clay, and refractory mining	1.04	0.611	0.15	0.164	0.233	569	569	10.4	0.002

[a] Values based on $1 million of input

[b] Metric tons of CO_2 equivalent

[c] Total air (point and non-point), water, land, and underground toxic releases; plus total toxic transactions into publicly owned treatment facilities and offsite transactions.

CHAPTER IV

CONCLUSIONS

Sustainable design of green roofs was incorporated into this three and a half month study through the use of minimal local energy and material flows. These ideas were executed but consideration was given since winter conditions were present. This implied more maintenance versus a spring or fall planting. For instance a frost blanket was used periodically, mostly in December and January with a minimum of a day to a maximum of a week the boxes were covered on any one occasion. This was to ensure survival on significantly colder days (30-40 degree temperatures). Regular maintenance of the green roofs consisted of irrigation and weeding. The plots were hand watered a total of six times with 340 mL of potable water. Morning watering was preferred but not strictly followed as time and temperature often dictated the schedule. By March 23 the vegetation had received approximately 3.097 in of rainfall based on local weather data. Occasional weeding in the topsoil was conducted though very minor. Weeding occurred primarily as a measure to help with identifying the grasses planted. Efforts to utilize local, native, recycled, and reused materials was accomplished for the drainage, substrate, and vegetation layers. One exception was the smaller amount of aggregate in the topsoil drainage layer which therefore signals a diligent design ethic necessary for salvaged and recycled materials in green roofs.

The temperature differences between the substrate and ambient temperatures did not provide any conclusive results, agreeing with much of today's current research. All substrate pH values became more acidic; though, the greater changes in the shale and concrete versus the topsoil show potential issues regarding the addition of organic material in stone substrates. However, the pH levels were unexpected for the concrete substrate as it was assumed it would remain alkaline longer even with the compost helping to moderate.

Sedum and grass growth correlated in all boxes except the topsoil. *Sedum* growth was the greatest in the topsoil while grass growth was the lowest with blue grama not present in three plots (6 in and 8 in). Initially blue grama began sprouting in the topsoil plots but died off. A probable explanation for this is that a month into the study the layers, including substrate, were disturbed in all plots to correct an oversight in the drainage layer. However, cold temperatures and/or improper planting could have also been responsible. It can be concluded that buffalograss is more tolerable to cold temperatures, little irrigation, and habitat disruption (all characteristics of a green roof) than blue grama. Drainage of the green roofs was not measured but the shale and concrete both exhibited quick draining properties versus the topsoil.

The EIO-LCA confirmed the concrete a better substrate on one assumption. Within the "Other maintenance and repair construction" sector a number of its subsets involve very intense construction projects (single/mutli-family home development, commercial and industry construction). As mentioned in the results, the subset most suitable for the crushed concrete was “wrecking and demolition contractors.” Therefore, it is assumed the wrecking sector is a significantly smaller proportion of its total sector resulting in fewer environmental impacts (GWP and toxic releases/transfers); and thus making concrete better than shale or gravel.

Overall, *sedum* and buffalograss had successful overwintering growth whereas the blue grama proved more sensitive. The vegetation was planted off-season and therefore its ability to survive concludes these native species, primarily buffalograss and the *sedum* (coastal stonecrop), as ideal green roof vegetation. The shale and concrete were the most successful in establishing overall vegetation. The shale was mined regionally but is considered a typical commercial product. The concrete represented the recyclable substrate and the topsoil as the local substrate. From the study it can be determined the shale as an acceptable substrate if locally or regionally mined; as this could help to lower its GWP and total energy requirement. The best design choice would be the recycled crushed concrete as it allowed for good vegetation growth, was local and reused which further lowers its environmental impacts.

All these results have been deduced from a study less than four months which is atypical of a green roof study. Therefore, continued measurements will continue to be taken but these present results provide a glimpse into early data for local, recyclable substrates and plant species for a subtropical green roof.

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APPENDIX

The following are images taken: 12/28/2008, 1/26/2009, 2/5/2009, 2/19/2009, 3/5/2009, and 3/23/2009. They represent a week after planting, a month and then about two week intervals for the last four dates.

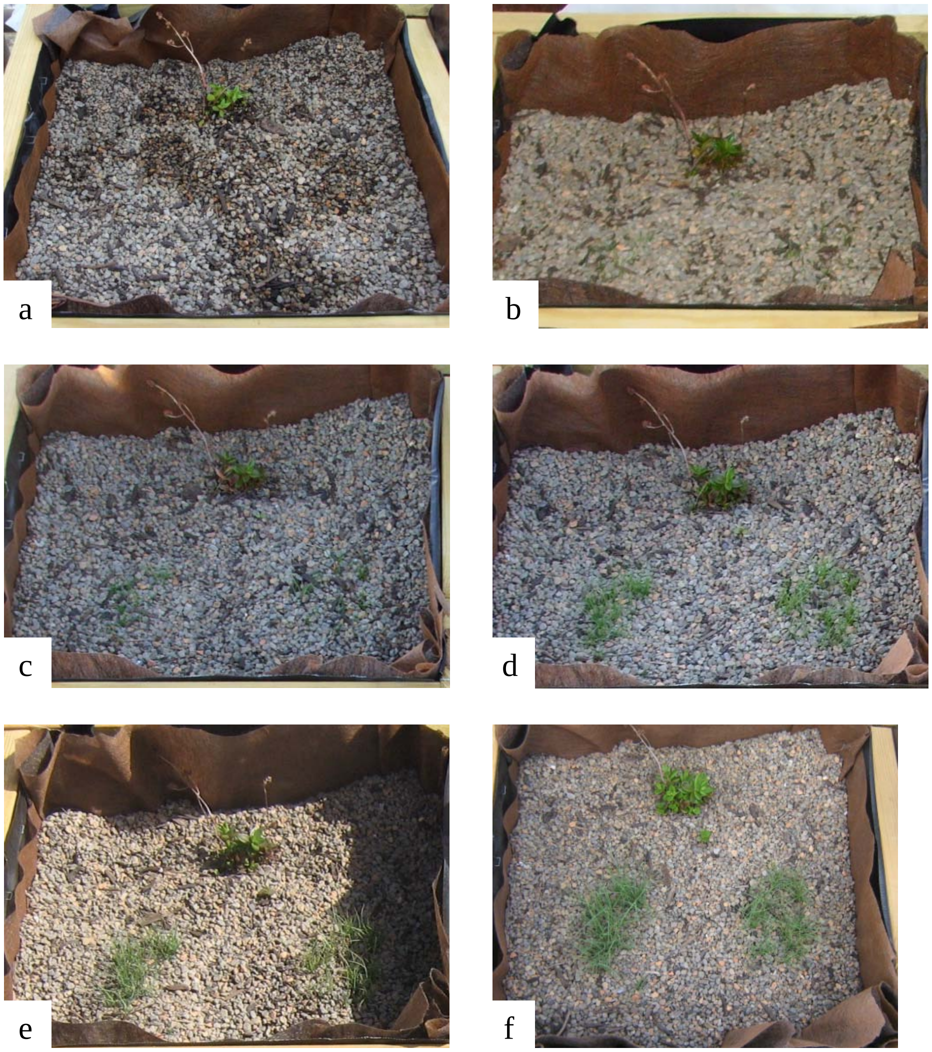

Fig. A – Overall vegetation growth in shale box, plot 1 for: (a) 12/28, (b) 1/26, (c) 2/5, (d) 2/19, (e) 3/5, (f) 3/23.

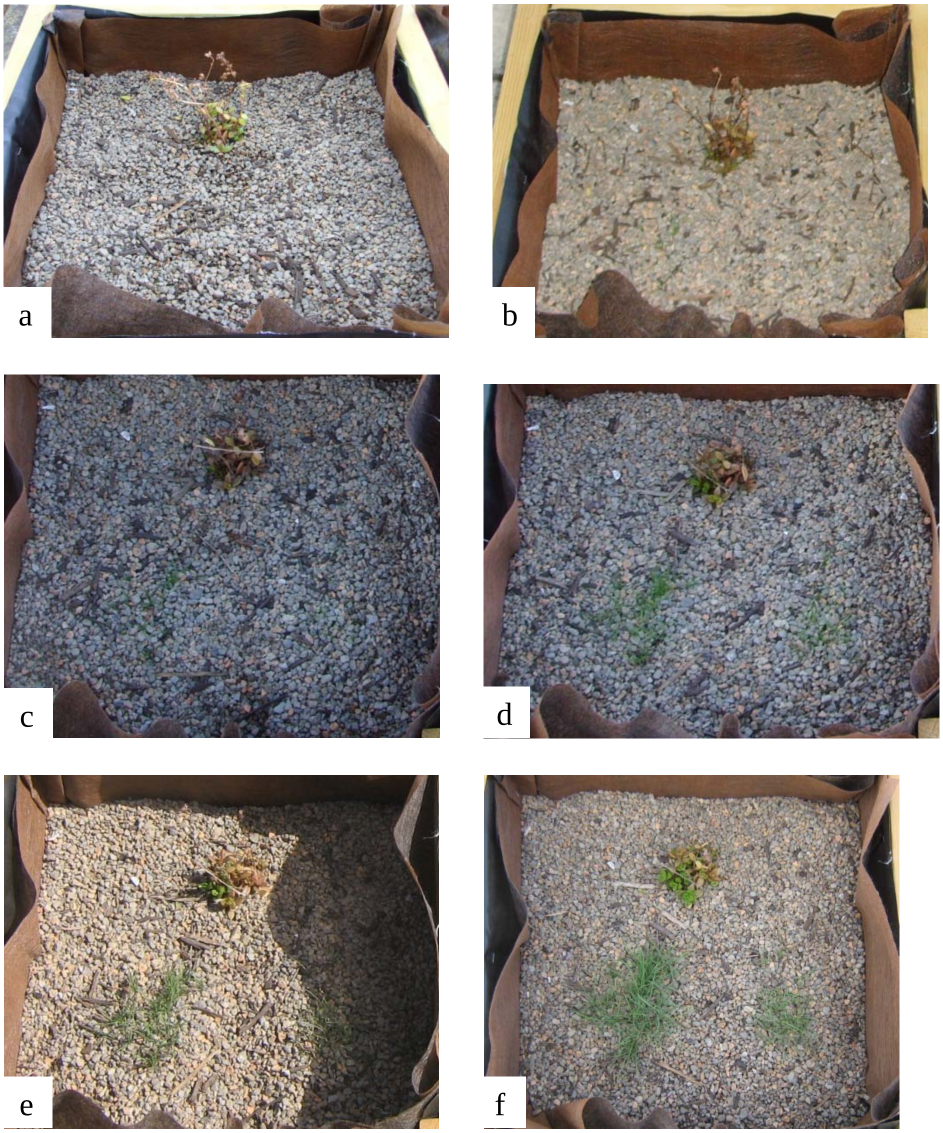

Fig. A – Overall vegetation growth in shale box, plot 2 for: (a) 12/28, (b) 1/26, (c) 2/5, d) 2/19, (e) 3/5, (f) 3/23.

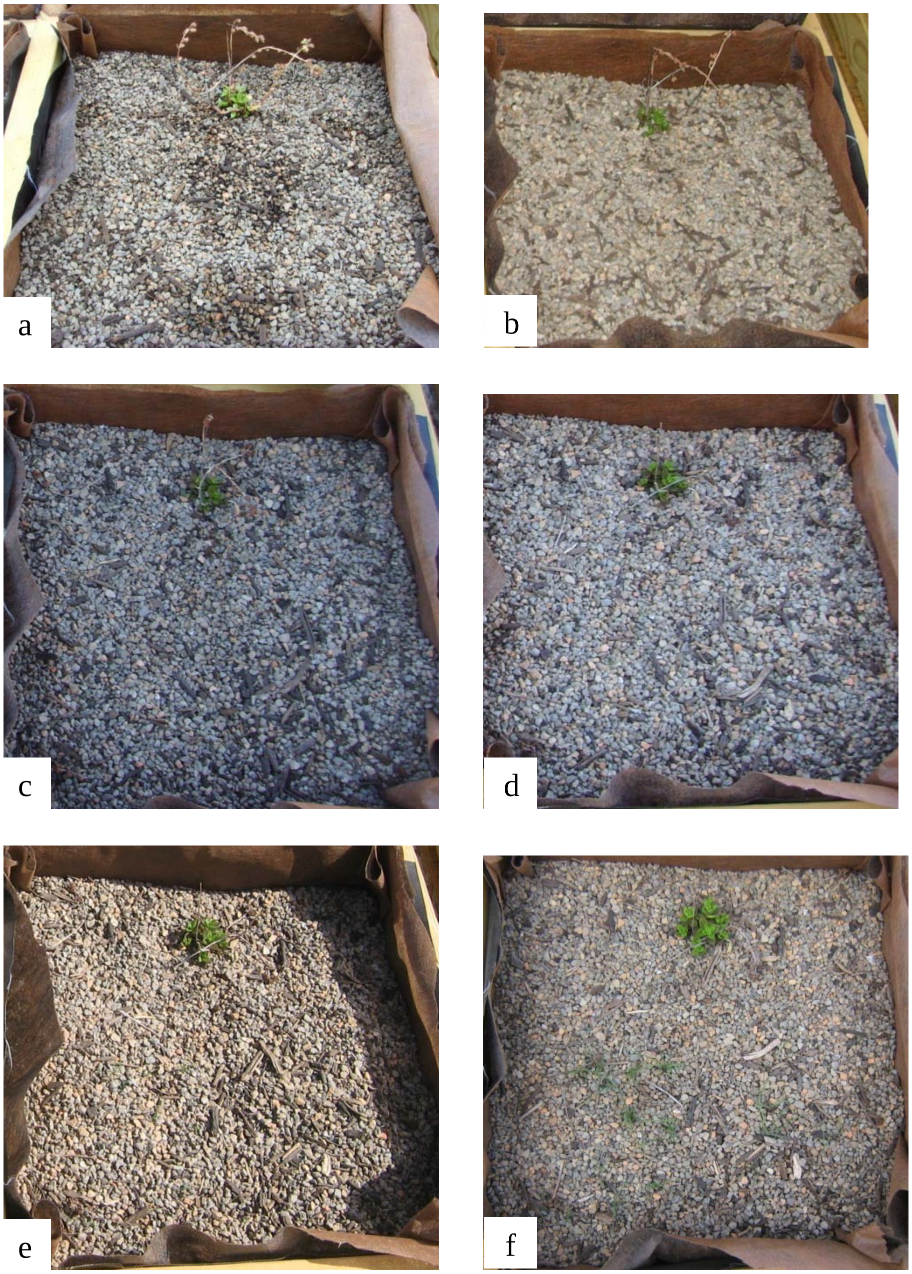

Fig. A – Overall vegetation growth in shale box, plot 3 for: (a) 12/28, (b) 1/26, (c) 2/5, (d) 2/19, (e) 3/5, (f) 3/23.

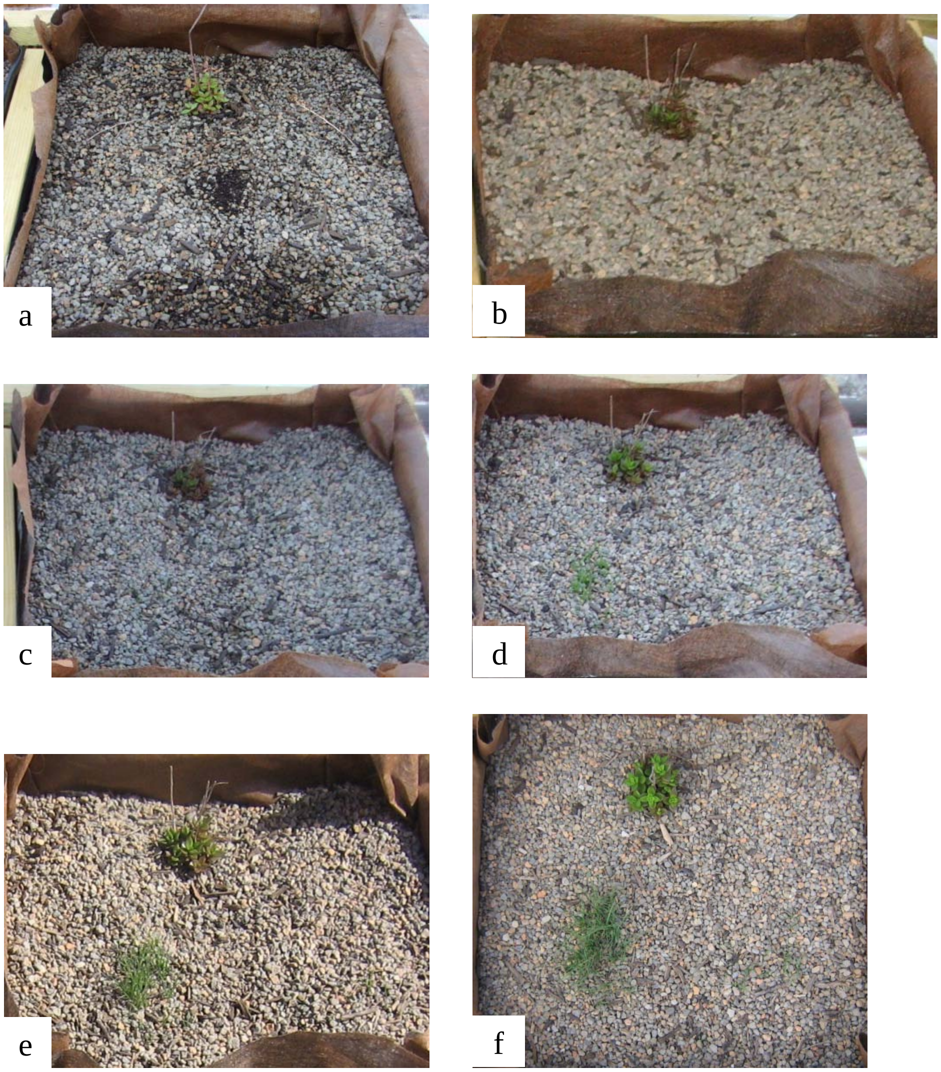

Fig. A – Overall vegetation growth in shale box, plot 4 for: (a) 12/28, (b) 1/26, (c) 2/5, (d) 2/19, (e) 3/5, (f) 3/23.

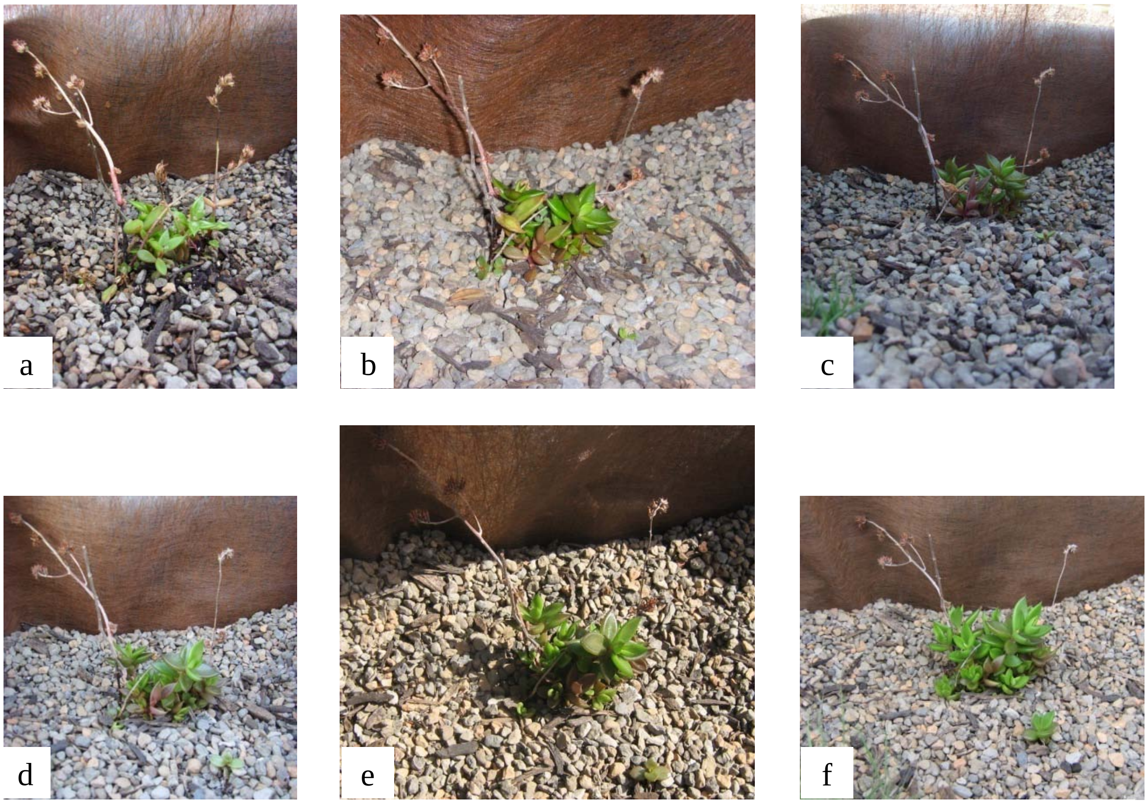

Fig. A – *Sedum* growth in shale box, plot 1 for: (a) 12/28, (b) 1/26, (c) 2/5, (d) 2/19, (e) 3/5, (f) 3/23.

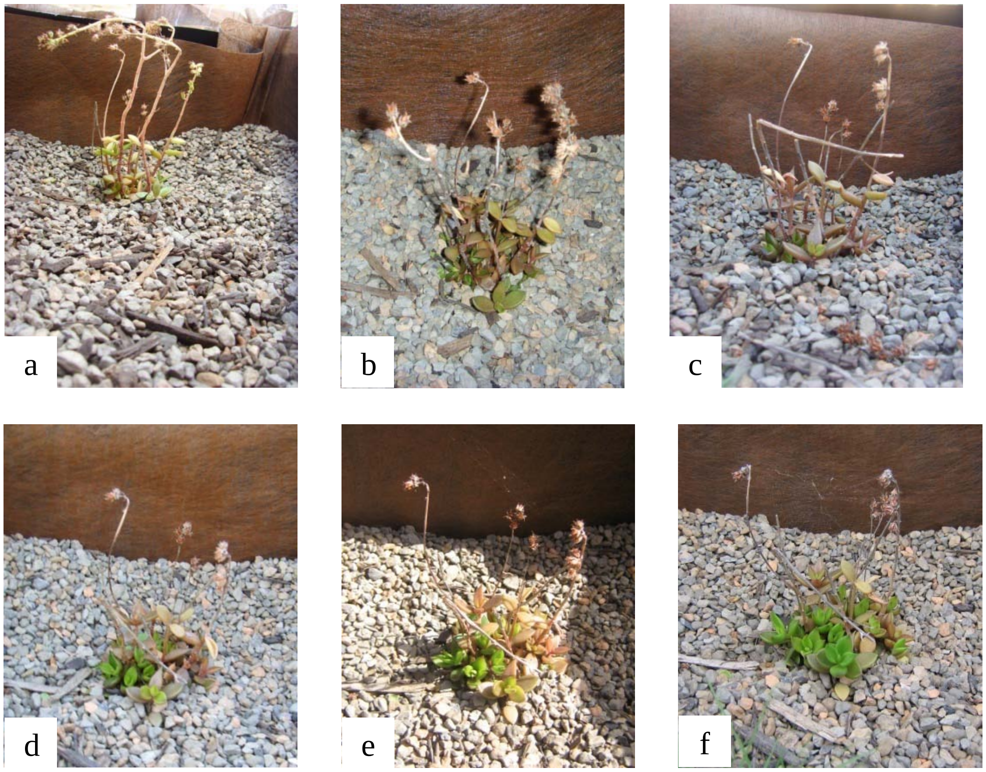

Fig. A – *Sedum* growth in shale box, plot 2 for: (a) 12/28, (b) 1/26, (c) 2/5, (d) 2/19, (e) 3/5, (f) 3/23.

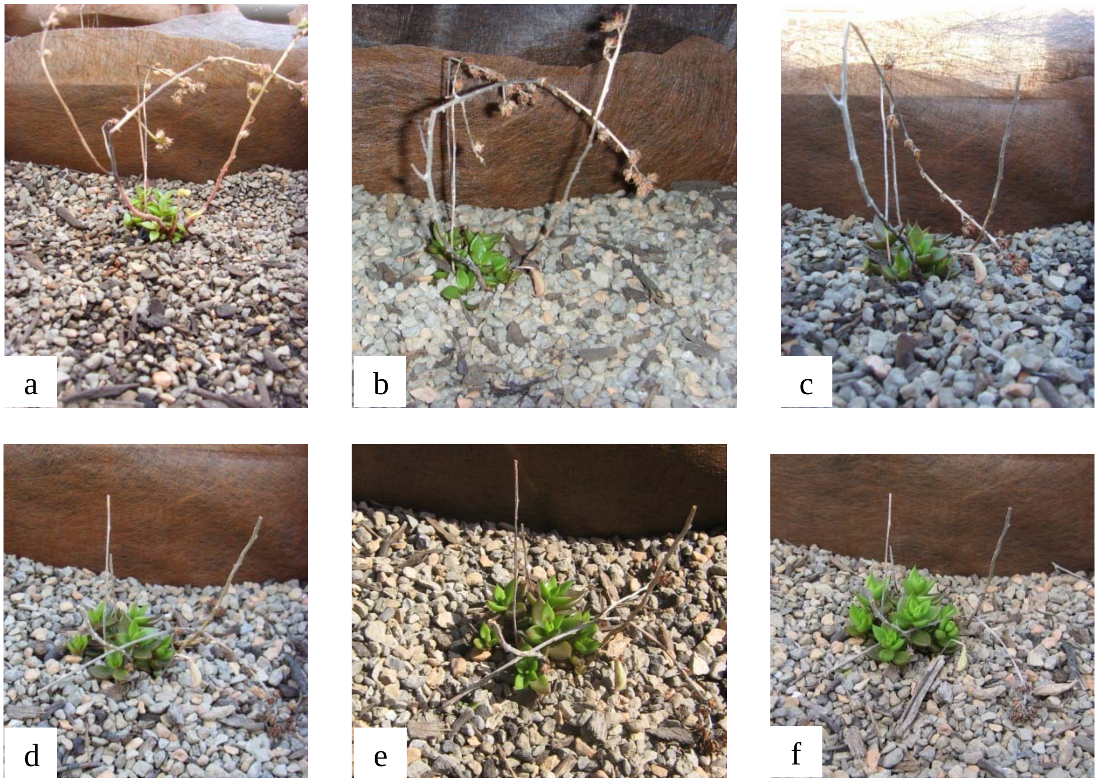

Fig. A – *Sedum* growth in shale box, plot 3 for: (a) 12/28, (b) 1/26, (c) 2/5, (d) 2/19, (e) 3/5, (f) 3/23.

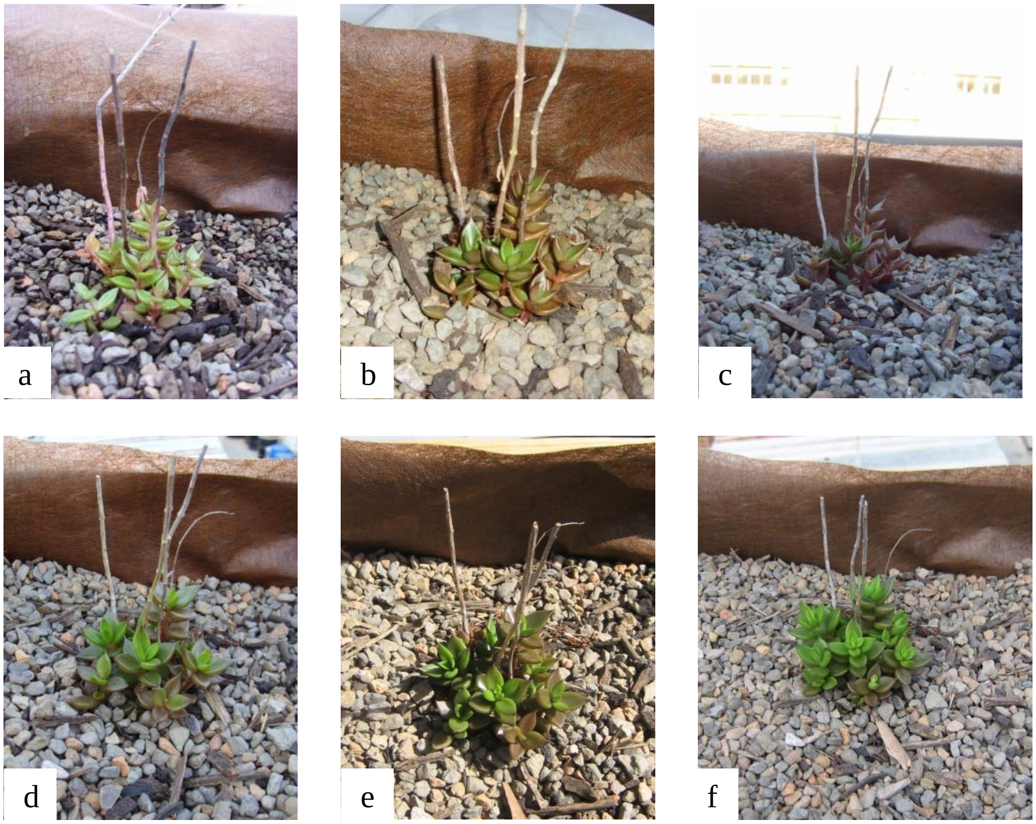

Fig. A – *Sedum* growth in shale box, plot 4 for: (a) 12/28, (b) 1/26, (c) 2/5, (d) 2/19, (e) 3/5, (f) 3/23.

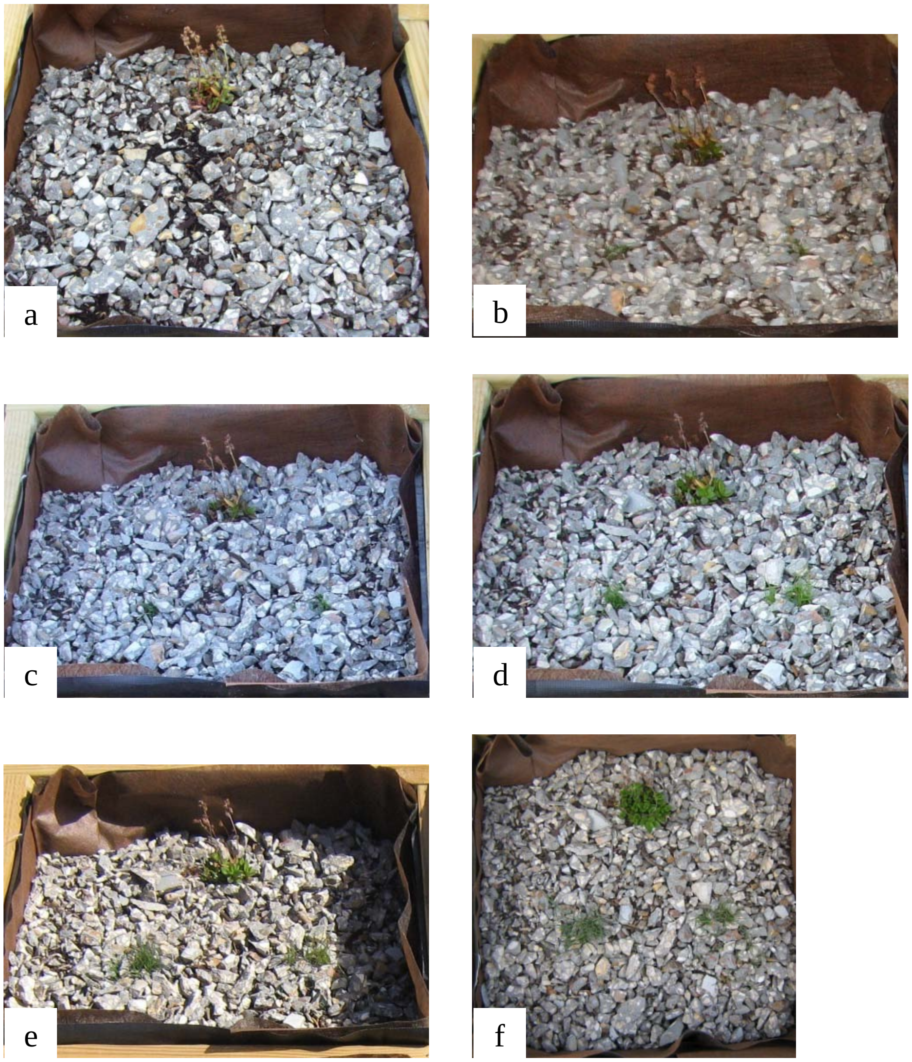

Fig. A – Overall vegetation growth in concrete box, plot 1 for: (a) 12/28, (b) 1/26, (c) 2/5, (d) 2/19, (e) 3/5, (f) 3/23.

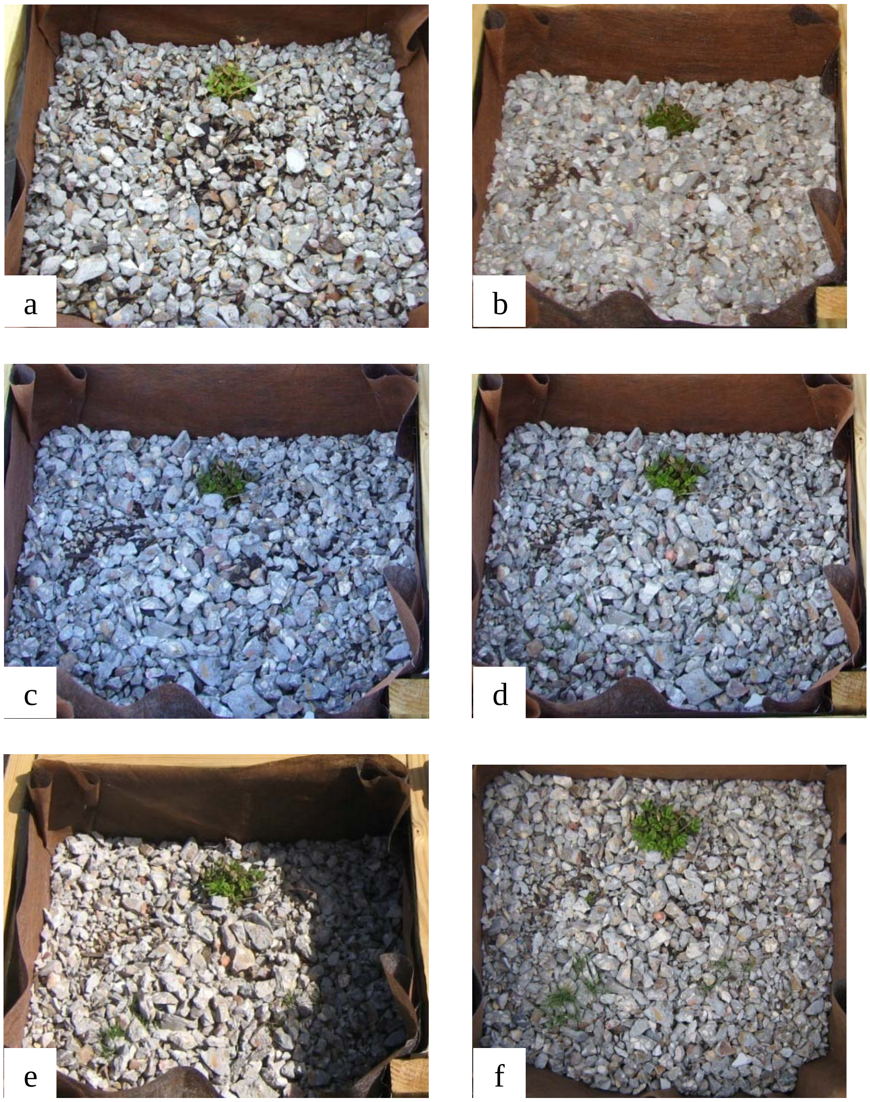

Fig. A – Overall vegetation growth in concrete box, plot 2 for: (a) 12/28, b) 1/26, (c) 2/5, (d) 2/19, (e) 3/5, (f) 3/23.

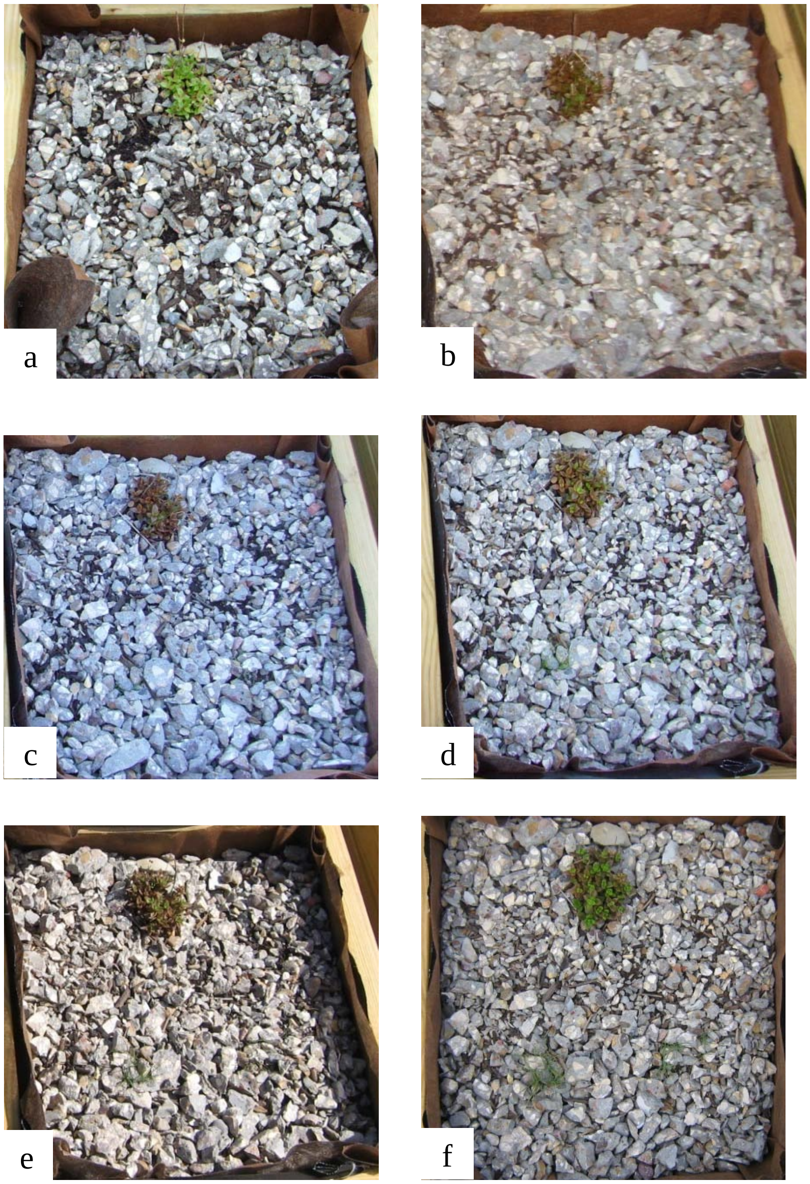

Fig. A – Overall vegetation growth in concrete box, plot 3 for: (a) 2/28, (b) 1/26, (c) 2/5, (d) 2/19, (e) 3/5, (f) 3/23.

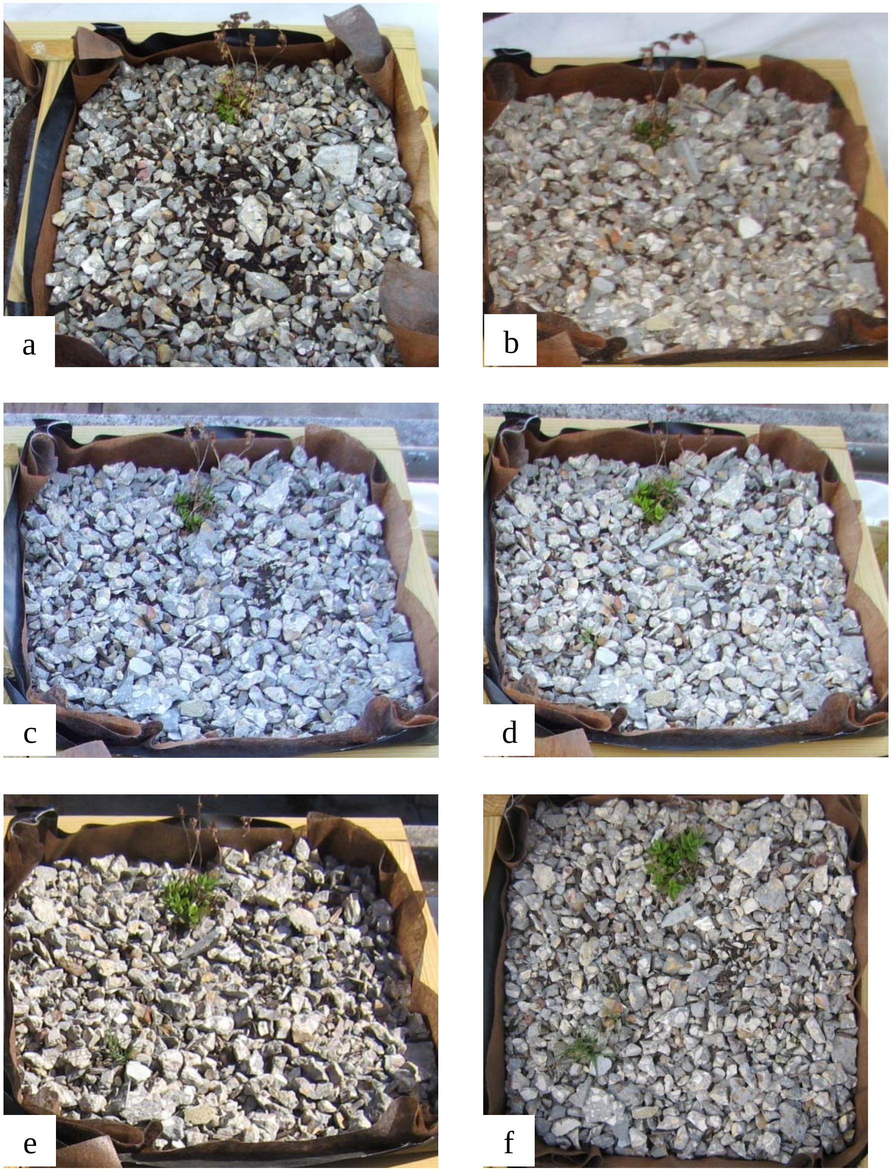

Fig. A – Overall vegetation growth in concrete box, plot 4 for: (a) 12/28, (b) 1/26, (c) 2/5, (d) 2/19, (e) 3/5, (f) 3/23.

Fig. A – *Sedum* growth in concrete box, plot 1 for: (a) 12/28, (b) 1/26, (c) 2/5, (d) 2/19, (e) 3/5, (f) 3/23.

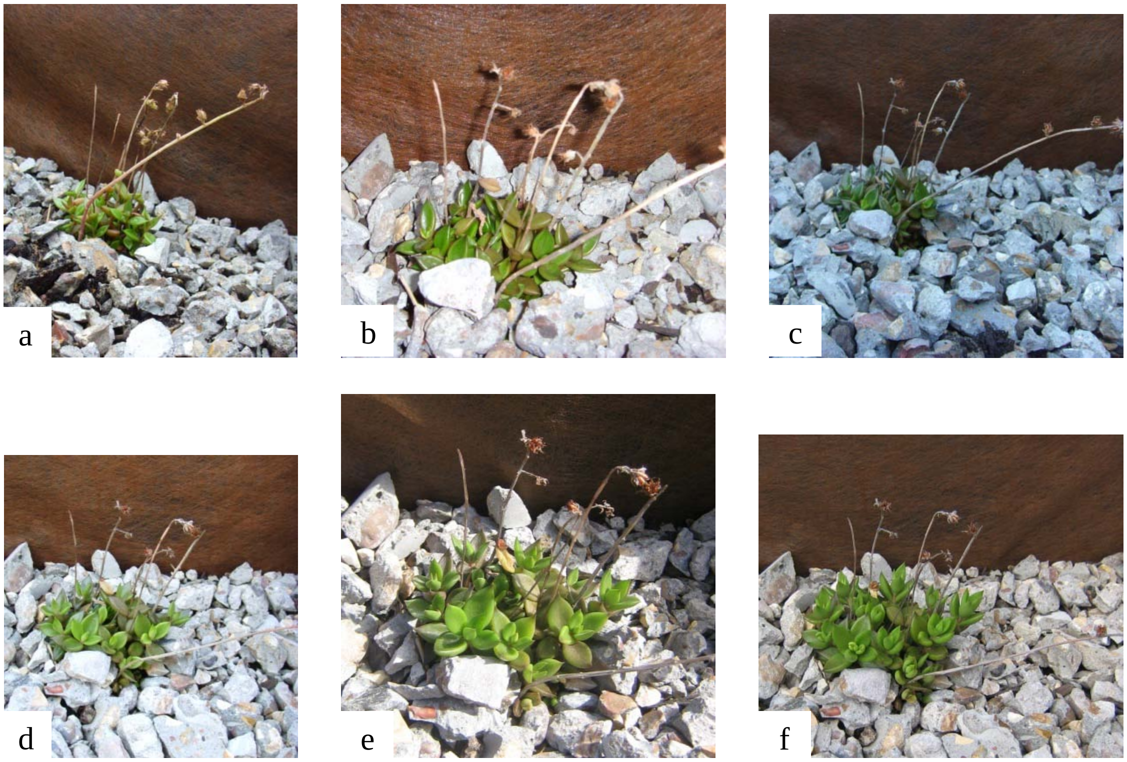

Fig. A – *Sedum* growth in concrete box, plot 2 for: (a) 12/28, (b) 1/26, (c) 2/5, (d) 2/19, (e) 3/5, (f) 3/23.

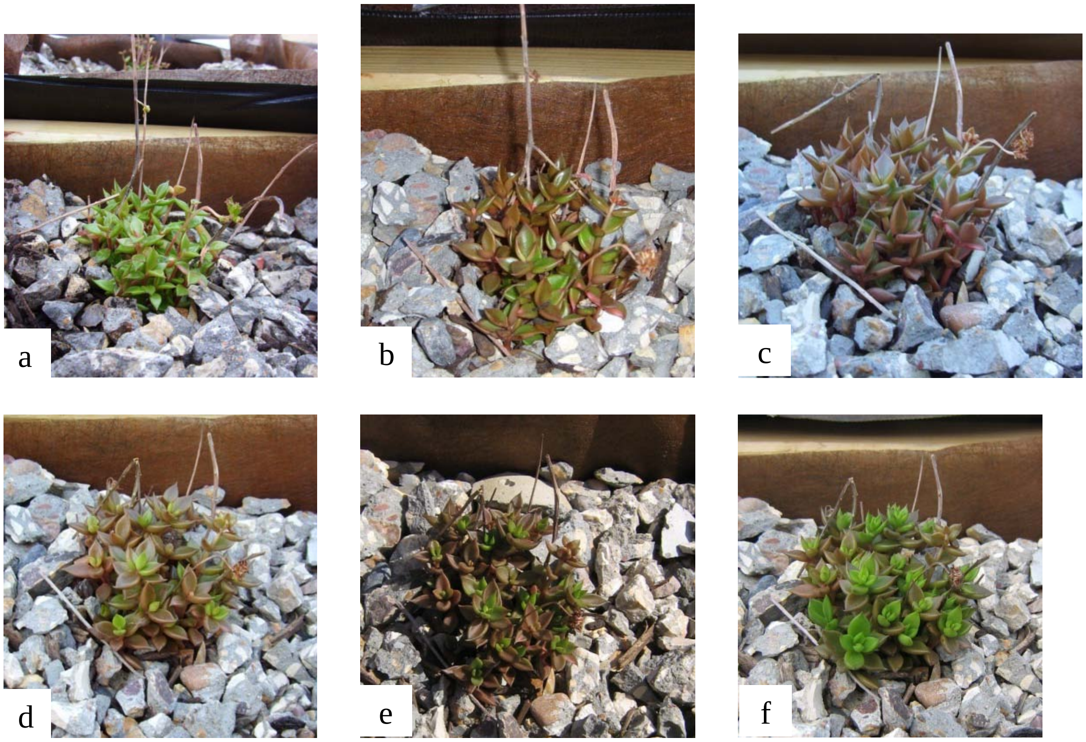

Fig. A – *Sedum* growth in concrete box, plot 3 for: (a) 12/28, (b) 1/26, (c) 2/5, (d) 2/19, (e) 3/5, (f) 3/23.

Fig. A – *Sedum* growth in concrete box, plot 4 for: (a) 12/28, (b) 1/26, (c) 2/5, (d) 2/19, (e) 3/5, (f) 3/23.

Fig. A – Overall vegetation growth in topsoil box, plot 1 for: (a) 12/28, (b) 1/26, (c) 2/5, (d) 2/19, (e) 3/5, (f) 3/23.

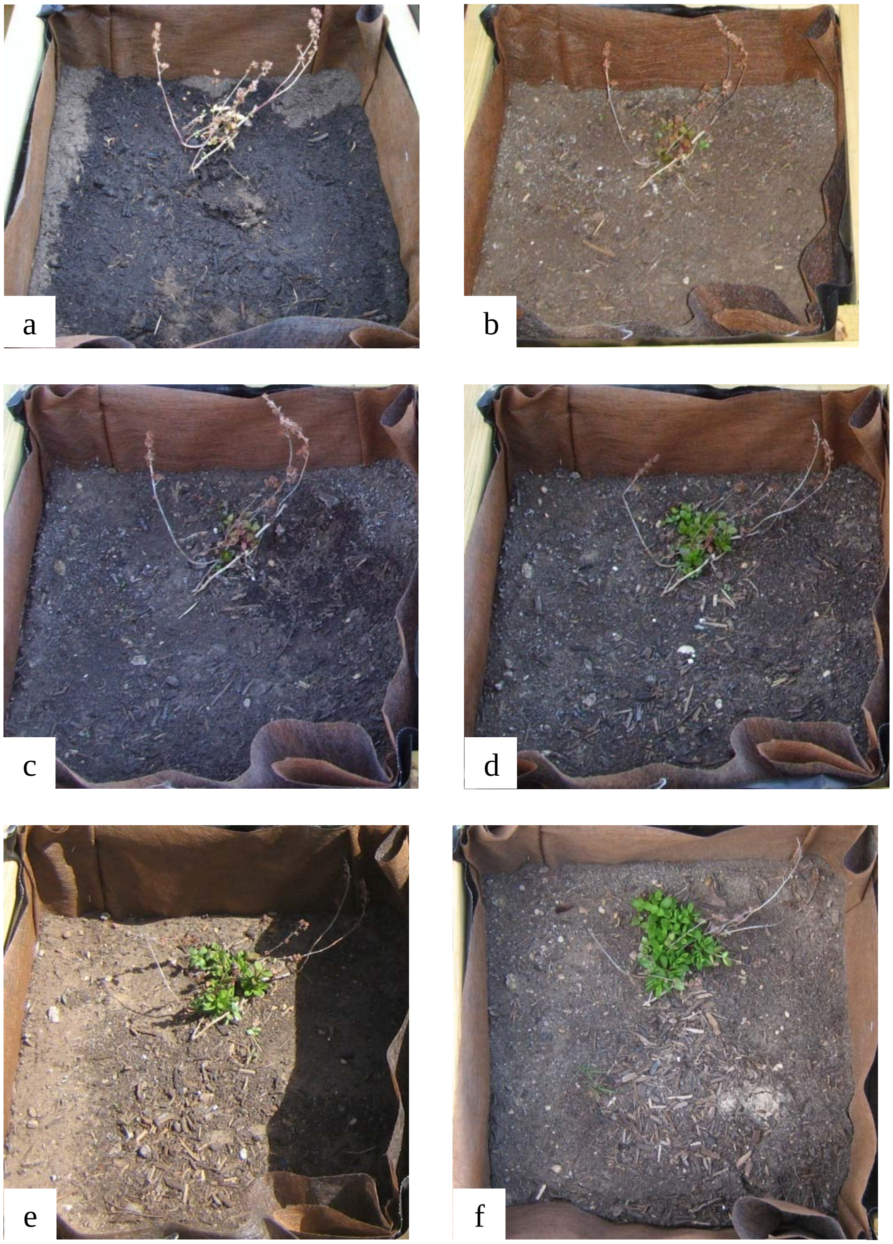

Fig. A – Overall vegetation growth in topsoil box, plot 2 for: (a) 12/28, (b) 1/26, (c) 2/5, (d) 2/19, (e) 3/5, (f) 3/23.

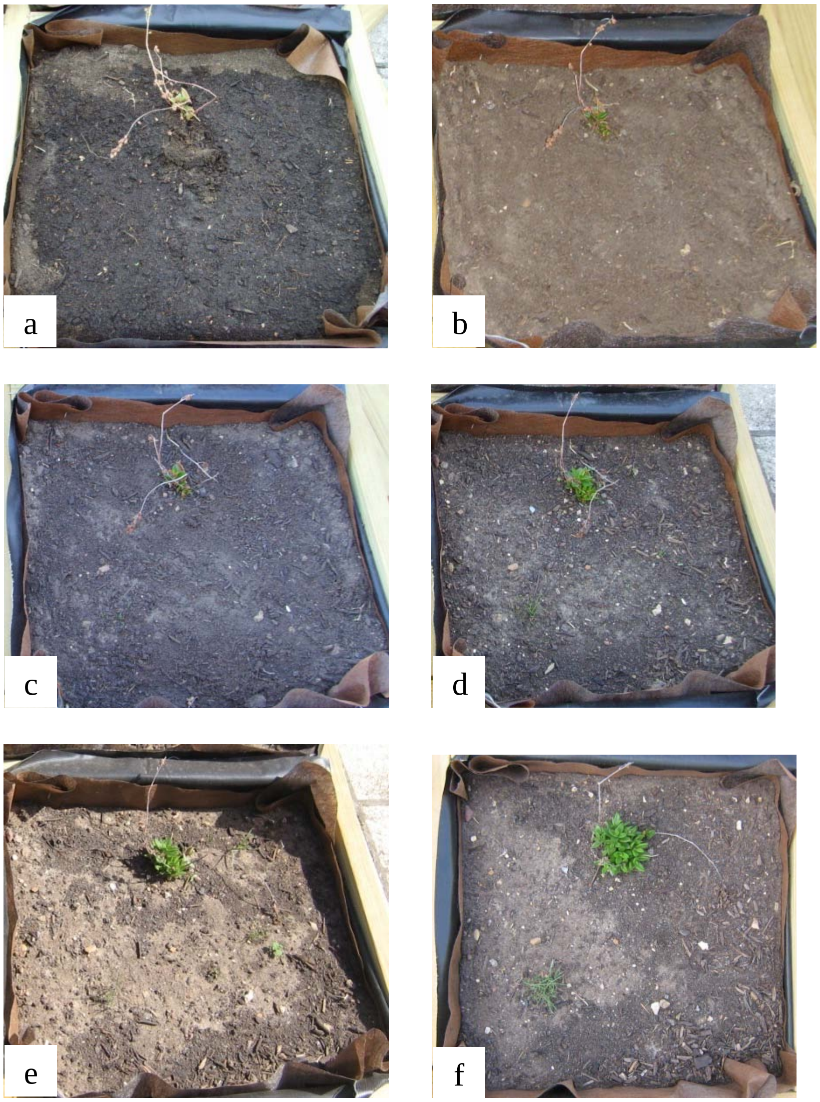

Fig. A – Overall vegetation growth in topsoil box, plot 3 for: (a) 12/28, (b) 1/26, (c) 2/5, (d) 2/19, (e) 3/5, (f) 3/23.

Fig. A – Overall vegetation growth in topsoil box, plot 4 for: (a) 12/28, (b) 1/26, (c) 2/5, (d) 2/19, (e) 3/5, (f) 3/23.

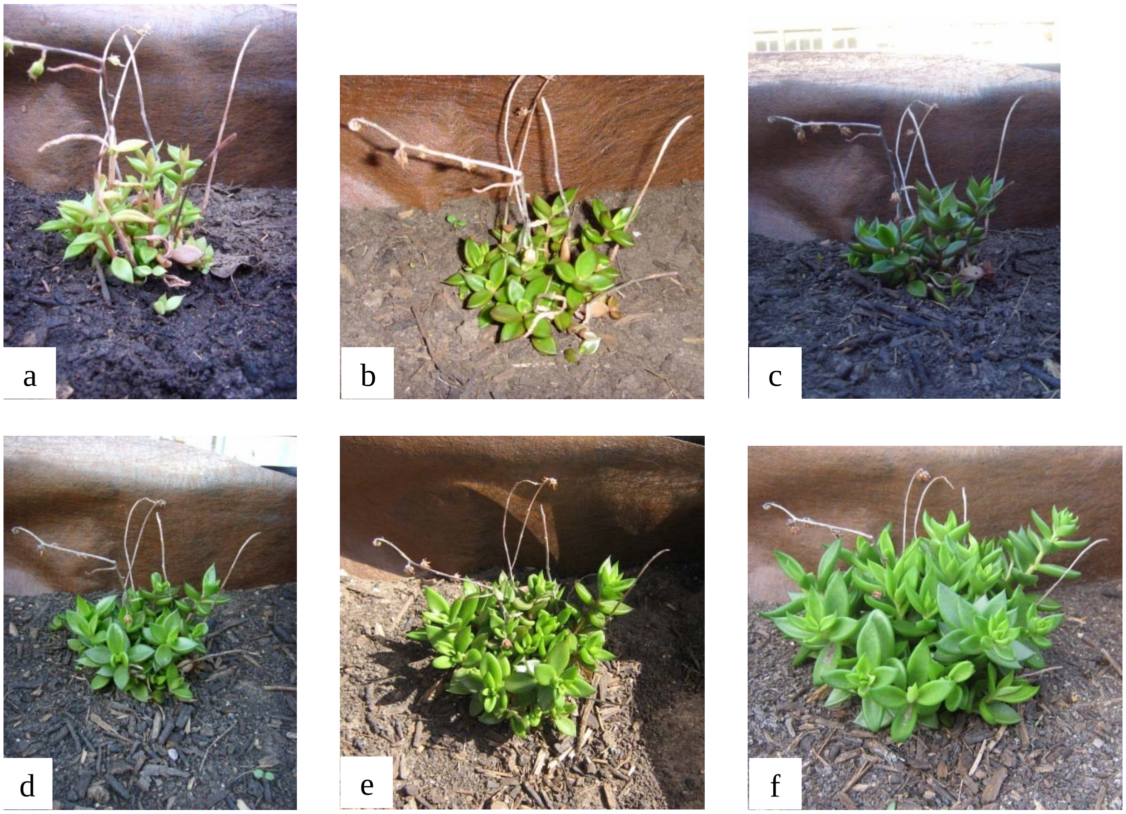

Fig. A – *Sedum* growth in topsoil box, plot 1 for: (a) 12/28, (b) 1/26, (c) 2/5, (d) 2/19, (e) 3/5, (f) 3/23.

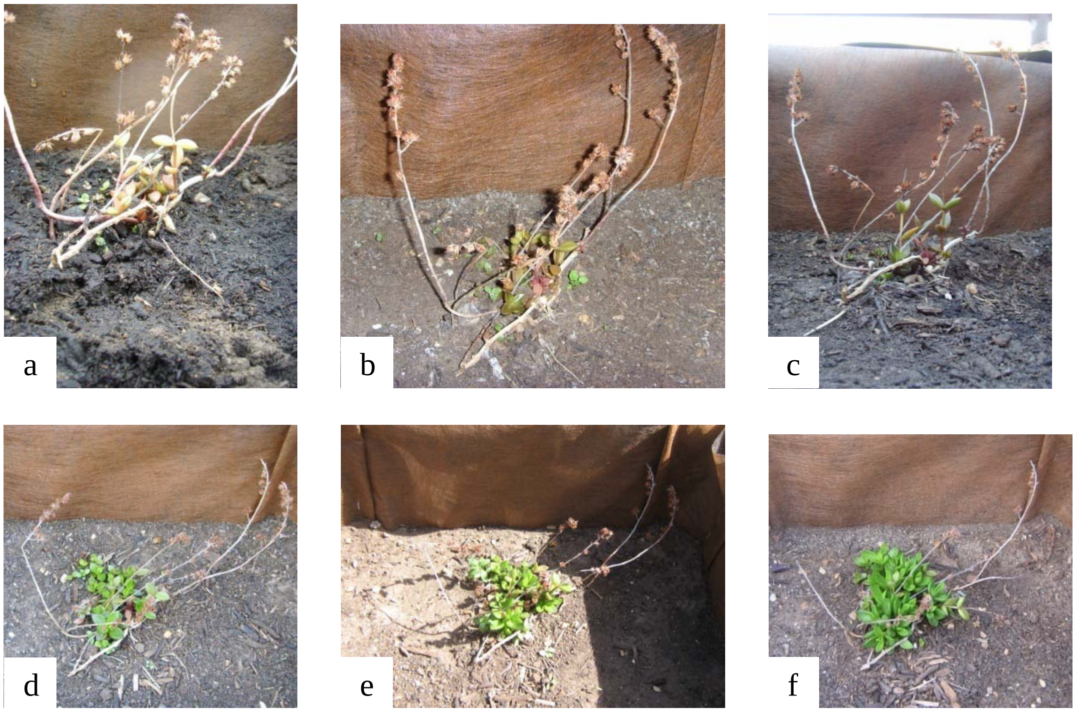

Fig. A – *Sedum* growth in topsoil box, plot 2 for: (a) 12/28, (b) 1/26, (c) 2/5, (d) 2/19, (e) 3/5, (f) 3/23.

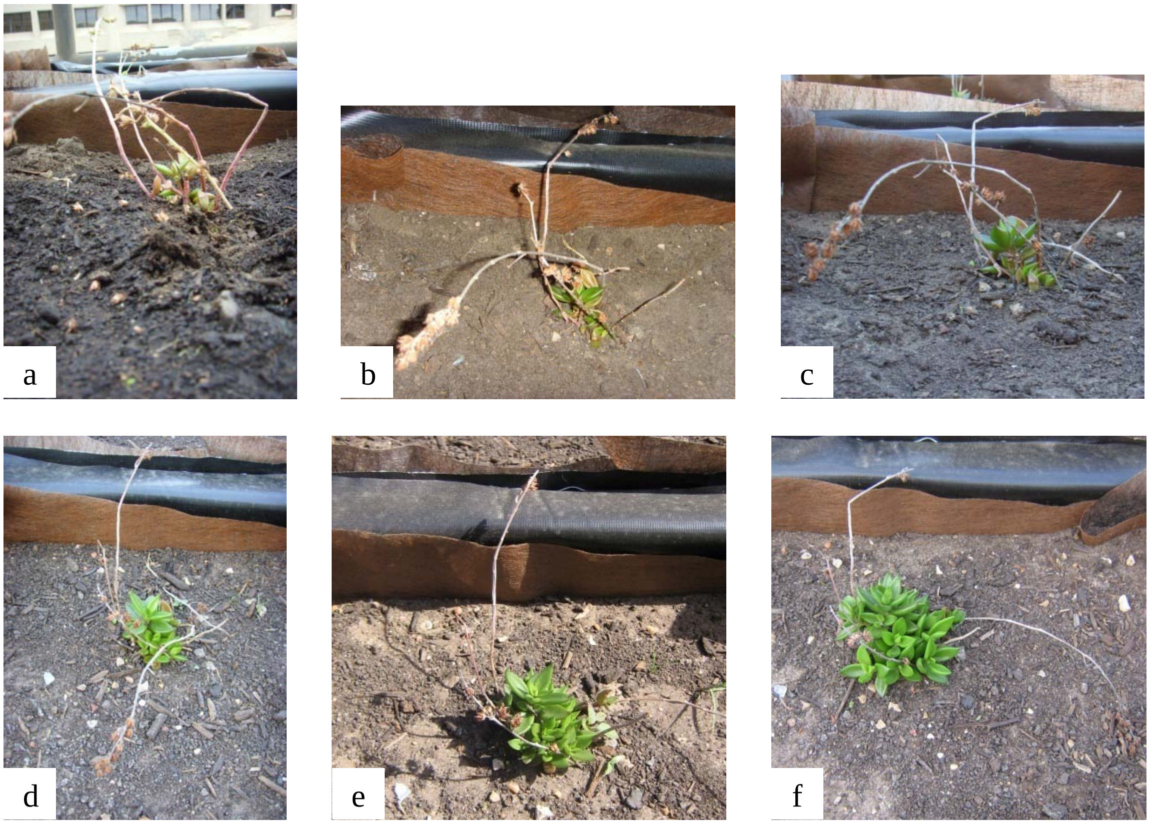

Fig. A – *Sedum* growth in topsoil box, plot 3 for: (a) 12/28, (b) 1/26, (c) 2/5, (d) 2/19, (e) 3/5, (f) 3/23.

Fig. A – *Sedum* growth in topsoil box, plot 4 for: (a) 12/28, (b) 1/26, (c) 2/5, (d) 2/19, (e) 3/5, (f) 3/23.

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