Plant Growth and Root Zone Management of Greenhouse Grown Succulents

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ABSTRACT

Effects of media, soil moisture, fertility rate, and plant growth regulators on plant growth were investigated for 13 taxa of succulents.

Media: Liners were grown in five common greenhouse substrates: 80% peat, 60% bark + 30% peat moss, 80% pine bark/20% Permatil (v/v), 100% composted pine bark, or whole tree substrate until market ready. Overall, higher percentage bark mixes yielded smaller plants, with lower shoot dry weights, shoot heights and widths.

Soil Moisture: Liners were potted into a 60% bark/30% peat soilless potting mix. In group 1 , irrigation to container capacity occurred when volumetric soil moisture content fell below 30%, 20%, or 10%,. Group two (seven species) irrigation thresholds were shifted to 35%, 25%, and 15%. Effects of irrigation rate were significant in three of the 13 species studied, and those effects were species-specific.

Fertility Rate: Liners were potted into60% bark/30% peat substrate. Fertility reatments in group were 0, 50, 100, or 200 $mg{\cdot}L^{-1}$ nitrogen. Group 2 plants received treatments of 50, 150, 250, or 350 $mg{\cdot}L^{-1}$ nitrogen. Four of the 11 species studied were affected by nitrogen rate, with rates up to 200 $mg{\cdot}L^{-1}$ generally producing the largest plants.

PGRs: Seven species were potted into a 60% bark/30% peat substrate. Group one plants were treated with a foliar application of benzyladenine (Configure) at rates of 0, 400, 800, or 1600 $mg{\cdot}L^{-1}$. Group 2 plants were treated either BA at 0, 250, 500, or 1000 $mg{\cdot}L^{-1}$, dikegulac sodium (Augeo) at 400, 800, or 1600 $mg{\cdot}L^{-1}$, or a tank mix of 500 $mg{\cdot}L^{-1}$ Configure and 800 $mg{\cdot}L^{-1}$ Augeo.   BA caused an increase in branches leaders or offsets in two species.

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Introduction

"It is probably impossible to define what constitutes a *succulent plant"*(Eggli, 2002). The term 'succulent' can refer to a broad range of plant species and hybrids from many families. Typically, succulents are found in arid or semi-arid regions, though plants with succulent characteristics can be found all over the world. Succulents have adapted to survive in environments where water is not constantly available; therefore they may survive in areas where water is only available intermittently, or at certain times of the year (Sajeva and Costanzo, 2000). The greatest diversity of succulents originates from the southern regions of Africa, particularly the Cape Province area. The American continents are home to several species of succulent plants as well, mostly in the Cactacea and Agavacea families (Sajeva and Costanzo, 2000).

A succulent is a plant that possesses at least one succulent tissue. A succulent tissue is one that provides at least a temporary storage of usable water, which makes the plant independent from external water sources (Willert et al., 1990). With these water saving tissues, as well as a metabolic pathway known as Crassulacean Acid Metabolism (CAM), succulents tend to retain more moisture in the media for a longer period of time than herbaceous species (Bousselot et al., 2011).

Crassulacean acid metabolism (CAM) is a classic example of a metabolic adaptation to environmental stress (Winter and Smith, 1996). Put simply, during periods of moisture deficit, CAM plants close their stomata during the day and open them at night when transpiration rates decline (Bousselot et al., 2011). CAM plants take up CO_2 from the atmosphere predominantly at night, and then assimilate that CO_2 into carbohydrates during the following period of light (Winter and Smith, 1996). This mechanism improves the ability of plants to assimilate carbon in water-limited environments. CAM is widespread among vascular plants, especially in succulents from arid regions and in tropical epiphytes (Winter and Smith, 1996).

Taxa Studied

Table 1.1. Alphabetic listing of species studied by genus. Family, and origin (or known parentage) included to the right.

Taxa	*Family*	*Origin*	*Citation*
Aeonium 'Kiwi'	Crassulaceae	*Haworthii* Hybrid	San Marcos Growers, 2011
Aeonium arboreum 'Zwartkop'	Crassulaceae	Morocco, Canary Islands	Sajeva and Costanzo, 2000
Agave 'Blue Glow'	Agavaceae	Hybrid *A. ocahui x A. attenuata*	San Marcos Growers, 2011
Agave geminiflora 'Rasta Man'	Agavaceae	Nayarit, Mexico	Gentry, 1982
Aloe 'Fire Ranch'	Liliaceae	Hybrid	Sajeva and Costanzo, 2000
Aloe 'Grassy Lassie'	Liliaceae	Hybrid	Sajeva and Costanzo, 2000
Aloe variegata 'Gator'	Liliaceae	Cape Province, South Africa	Sajeva and Costanzo, 2000
Crassula coccinea 'Campfire'	Crassulaceae	Cape Province, South Africa	Sajeva and Costanzo, 2000
Dyckia 'Burgundy Ice'	Bromeliaceae	Hybrid	Sajeva and Costanzo, 2000
Echeveria 'Afterglow'	Crassulaceae	Hybrid *Echeveria cante x E. shaviana*	San Marcos Growers, 2011
Echeveria 'Violet Queen'	Crassulaceae	*E. elegans* Hybrid	San Marcos Growers, 2011
Kalanchoe thyrsiflora 'Flapjacks'	Crassulaceae	Cape Province, South Africa	Sajeva and Costanzo, 2000
Senecio cephalophorus 'Blazin Glory'	Asteraceae	Northern Cape, South Africa	Egli, 2002

We studied thirteen taxa from 8 different genera as described below.

Agavaceae – (monocotyledons) contains about 18 genera, plants may be stemless, short stemmed, or tree like. Leaves are fleshy or fibrous, usually arranged in rosettes. Roots are fibrous and stoloniferous. They are native to America, Africa, India, Madagascar and Australia (Sajeva and Costanzo, 2000).

Agave (L.) 'Blue Glow.' A Proven Selections® hybrid, Proven Winners (2012) calls it a 'magnificent hybrid with red-tinged leaves.' The rosettes of foliage have a distinctly blue cast (Proven Winners, 2012). San Marcos Growers (2011) cites that it was bred by Kelly Griffin from *A. ocahui* (Gentry) and *A. attenuata* (Salm). Both of these species are members of the subgenus *Littaea,* group Amole and are native to Sonora and Jalisco, Mexico, respectively (Gentry, 1982).

Agave geminiflora (Tagliabue) 'Rasta Man.' 'Rasta Man' is a selection of *A. geminiflora* marketed by Proven Winners. It is a 'pincushion' type *Agave* from the subgenus Littaea, group Filiferae. It is native to Nayarit, Mexico (Gentry, 1982). It forms dense green rosettes of relatively fine foliage, eventually producing hundreds of spines (Proven Winners, 2012).

Asteracea (Compositae) – (dicotyledons) contains roughly 1,100 genera characterized by flowers that are 'reduced and organized into an involucrate pseudanthium in the form of a head or a capitulum.' Plants are very diverse in morphology and distribution (Carr, 2009).

Senecio cephalophorus (Compton) 'Blazin' Glory.' 'Blazin Glory' is a Proven Winners selection of *S. cephalophorus* which is native to the Northern Cape Province of the Republic of South Africa. It displays soft, bluish green foliage and large, numerous orange flowers. *S. cephalophorus* is recognizable by pachycaul habit and leaf margins thickened on the bottom (Eggli, 2002).

Bromeliaceae – (monocotyledons) contains approximately 50 genera, both terrestrial and epiphytic. Leaves are basal, usually arranged in rosettes. Flowers are borne in spikes, with colored bracts. The Bromeliaceae family is native to tropical America (Sajeva and Costanzo, 2000).

Dyckia (Dyck) 'Burgundy Ice.' A *Dyckia* hybrid by Kelly Griffin, *Dyckia* is one of the most primitive Bromeliad genera, and contains some of the most cold-tolerant species. Most species of *Dyckia* are native to central Brazil, with some being found in other parts of South America (Bromeliad Society Houston, 2011). 'Burgundy Ice' is named for its deep purple foliage. Flowers are borne in spikes and have colored bracts (Sajeva and Costanzo, 2000).

Crassulaceae – (Dicotyledons) Crassulaceae contains 33 genera ranging from annual or perennial herbs or shrubs to small trees, most with succulent leaves. Members of Crassulaceae are widely distributed across several continents (Sajeva and Costanzo, 2000).

Aeonium arboretum (Linne) 'Zwartkop.' Proven Winners lists this plant as a hybrid while San Marcos Growers says it's a selction of *A. arboreum.* It is an upright growing plant with a fleshy, almost woody stem and rosettes of dark burgundy or purple foliage. Yellow, star shaped flowers form in long clusters from the center of rosettes on mature plants (San Marcos Growers, 2011). It's native to the Canary Islands (Eggli, 2003).

Aeonium (L.) 'Kiwi.' Rosettes of spoon–shaped leaves on short stems are primarily green with yellow and pink. Light yellow flowers appear in late summer (Proven winners, 2012). This *Aeonium* is considered to be an *A. haworthii* hybrid, but its origin is unknown (San Marcos Growers, 2011).

Crassula coccinea (L.) 'Campfire.' A branching succulent with light green propeller shaped leaves that mature to a bright red color (San Marcos Growers, 2011). Small, white flowers dispersed along the stem. Species native to Western Cape of the Republic of South Africa (Eggli, 2003).

Echeveria (De Candolle) 'Afterglow' displays a large rosette of fleshy leaves covered with a lavender colored powder, especially in ideal sun (Proven Winners, 2012). Large spikes of orange flowers emerge from below leaves or sometimes as terminal inflorescence. 'Afterglow' is a hybrid of *E. cante*

(Glass) and *E. shaviana* (Walther) (San Marcos Growers, 2011) which are native to Zacatecas and Nuevo Leon, Mexico, respectively (Eggli, 2003).

Echeveria 'Violet Queen.' A rosette forming succulent with gray foliage, 100 to 125 cm high, and each rosette is 150 to 200 cm across. Bred by Edward Orpet,' Violet Queen' is thought to be a hybrid of *E. elegans* (Rose) (San Marcos Growers, 2011). *E. elegans* is native to Hidalgo, Mexico (Eggli, 2003).

Kalanchoe thyrsifolia (Harvey) 'Flapjacks.' Fleshy, paddle-like leaves form rosettes in the shape of a clamshell. Fragrant, powdery white flowers are borne on a spike in early spring (Proven Winners, 2012). Leaves may be bright green to deep red, depending on light and moisture levels. It is a native to south-eastern Botswana and the Republic of South Africa (Eggli, 2003)

Liliaceae – (Monocotyledons). A large family of mostly herbaceous plants, Liliaceae contains a few tree-like species. This family is widespread in distribution and morphology. Some sources have split this family into several others, but Liliaceae (Aloaceae) is still accepted in a broad sense (Sajeva and Costanzo, 2000).

Aloe (L.) 'Fire Ranch.' Fleshy, strap-like green leaves borne in rosettes, 'Fire Ranch' bears numerous red-orange flowers on multiple spikes.

Aloe 'Grassy Lassie' has deep green, narrow, grass-like leaves with bright orange flowers. In full sun, foliage becomes a deep bronze (Proven Winners, 2012). A Kelly Griffin hybrid, its parentage is from South Africa (San Marcos Growers, 2011).

Aloe variegata (L.) 'Gator' has stem less rosettes up to 25 cm tall. Leaves green to brownish green with white spots arranged in bands. Pink flowers are borne on a spike up to 30 cm tall. It is native to Cape Province, Karoo, and Namaqualand, South Africa (Sajeva and Costanzo, 2000).

Media

Greenhouse crops are commonly grown in soilless media. The role of media is to replace soil by providing water, supplying nutrients, and permitting gas exchange of roots, and providing physical support for the plants (Fonteno, 1996). Most soilless media are usually blends of two or more components and the components and their ratios affect both the physical and chemical properties of the media (Fonteno, 1996). The primary components in most soilless growing media used in greenhouse production are peat and softwood bark (Wright and Browder, 2005). Common amendments include perlite, vermiculite and other aggregates. Some of these aggregates may include industrial minerals such as brick chips (Owen et al., 2007) or Permatil, an expanded shale product, to increase drainage and reduce media weight (Rowe et al., 2006).

Physical Properties

An important aspect of soilless media is their physical properties, namely air space, container capacity, and bulk density. These properties can have a significant impact on plant growth (Blythe and Merhaut, 2007), and can be determined for individual substrates by using the porometer developed at North Carolina State University. Air space is defined as the percent of the substrate volume that is filled with air after it is saturated and allowed to drain (Fonteno and Harden, 2003). Conversely, container capacity is the percent volume of a substrate that is filled with water after a container is saturated and allowed to drain (Fonteno and Harden, 2003). Bulk density is the ratio of the mass of dry solids in the mix to the volume of the substrate (Fonteno and Harden, 2003). Fonteno also notes total porosity as an important physical property determined using the porometer. Total porosity is the percent of a substrate that consists of pores (Fonteno and Harden, 2003).

There are no universally accepted standards for the physical properties of substrates, but suggested ranges are from 50% to 85% total porosity, 10% to 30% airspace, and a bulk density between 0.19 $g \cdot cm^{-3}$ and 0.7$g \cdot cm^{-3}$ (Bilderback et al, 2005).

Table 1.2. Physical properties of substrates used. Physical properties measured using the North Carolina State University porometer (Fonteno and Harden, 2003).

Substrate (Source)	Composition	Total Porosity (%)	Container Capacity (%)	Air Space (%)	Bulk Density (g/cm3)
100% Fafard 52 Mix (Conrad Fafard, Inc., Agawam, MA)	-60% Pine Bark -Sphagnum Peat Moss -Perlite -Vermiculite -Starter Fert	80.4	67.6	18.8	0.18
100% Pro-Mix BX Mycorrhizae (Premier Tech Horticulture, Quakertown, PA)	-80-85% Sphagnum Peat Moss -Perlite Vermiculite -Starter Fert.	87.4	61.6	19.8	0.11
100% Fafard Timba-Tec TT600 (Conrad Fafard, Inc., Agawam, MA)	-60% Proprietary Wood Substrate -Sphagnum Peat Moss -Aged Pine Bark -Starter Fert	85.7	61.7	23.9	0.16
100% Composted Pine Bark (Riverbend Nursery, Riner, VA)	100% Aged Pine Bark	83.7	59.4	24.5	0.20
80% composted pine bark/20% Permatil (Carolina Stalite Company, Salisbury, NC)	80% Aged Pine Bark 20% Permatil (By Volume)	75.7	53.4	22.2	0.34

Chemical Properties

Electrical conductivity (EC) measurements are used in greenhouse production as a measure of the nutrient content of the media (Scoggins and van Iersel, 2006). An increase in EC generally indicates that more fertilizer is being applied than the plant can use. Conversely, a falling EC shows that the plant is not receiving enough fertilizer for optimal growth (van Iersel, 1999).

pH is a measure of hydrogen ions in solution, recorded on a logarithmic scale from 0 to 14, with 7 being neutral. Anything above seven is known as basic or alkaline, while values below seven are considered acidic. The ability of plant roots to acquire and use nutrients is strongly influenced by pH (Mathers et al., 2007). The optimum substrate pH varies by species, but in general substrate pH should be between 5.4 and 6.8 (Mathers et al., 2007). High substrate pH may cause plants to exhibit deficiencies of aluminum, iron, boron, zinc, manganese, and other elements. Substrates with too low of a pH may cause plants to exhibit toxicities in iron, manganese, zinc, and copper, deficiencies in calcium or magnesium, and sensitivity to ammonium (Mathers et al., 2007).

Cation exchange capacity (CEC) is a measure of media's nutrient holding capacity. It refers to the exchange between cations in substrate solution and cations on negatively charged soil or organic colloids (Mathers et al., 2007). In soilless media, it is expressed as milliequivalents per hundred cubic centimeters (me/100cc) (Fonteno, 1996). The recommended CEC range for soilless substrate is between 6 and 15 me/100cc (Fonteno, 1996).

Substrate Moisture Content

Because managing water resources is one of the most important challenges in production (van Iersel et al., 2010), knowledge about plant tolerance to moisture stress is important (Bousselot et al., 2011). Irrigation management is important in ornamental crop production for reducing nutrient and pesticide laden runoff, producing high quality plants, and reducing overall production costs (Van Iersel et al., 2010). Irrigation management entails controlling the moisture content of the root zone and there are several methods for determining when to irrigate. Some of these methods include look and feel, gravimetric, timers, sensors, and models (Lieth, 1996).

Two of the most common direct methods for measuring soil moisture content are volumetric and gravimetric (Brady, 1990). Gravimetric measurements involve weighing a sample of moist soil, drying it at a temperature of 100°C to 110 °C and weighing it again. The water weight lost represents the moisture level of the moist sample (Brady, 1990). While this is a useful and accurate method for determining moisture content, it cannot be used on media containing live plants, as the oven drying would kill them (Lieth, 1996). Volumetric moisture content is defined as the volume of water associated with a given volume of dry solids (Brady, 1990). Another way of saying this is that volumetric moisture content is the percent of total pore space that is filled by water.

There are several types of electronic instruments available to measure volumetric water content. Most use dielectric measurements, which takes advantage of the differences in electrical permittivity between the soil (substrate), and the water within the soil (Bitelli, 2011). Some sensors, such as time-domain reflectometry (TDR) obtain this value by measuring the time it takes for an electromagnetic pulse to travel between a set of probes (Robinson et al., 2003). Another common sensor is a capacitance type sensor. Capacitance sensors also measure the dielectric constant of the soil, but do so with only one probe. To do so, they rely on the fact that water has a much higher dielectric constant than either air or dry soil (Morgan et al., 2010).

While there are optimal soil moisture levels for the growth of ornamental crops, imposition of specific levels has proved difficult (Kiehl et al., 1992). Optimal levels vary based on the crop being grown, the media used and other factors. Plant growth is generally inhibited at moisture levels below 15%, but can vary widely by species. Petunias (*Petunia spp.* Juss.), for example show drought stress at moisture levels below 25% (Van Iersel et al., 2010) but moisture contents between 24% and 34% are ideal for optimal growth in other herbaceous crops such as snapdragon (*Antirrhinum spp.* L.) (Kiehl et al., 1992). Succulents, such as sedums, generally retain moisture in the substrate longer than other herbaceous plants, and can tolerate lower substrate moisture contents before indicating stress (Bousselot et al., 2011).

Fertility

Little species-specific information is available on the nutritional needs of containerized herbaceous perennials (Scoggins, 2005). Even less is available on the needs of containerized succulents. That being said, the goal of any fertilization program is to provide the plant with sufficient, but not excessive levels of nutrition (Scoggins, 2005).

Plants require 17 essential elements, three of which are obtained naturally from water and air while all others must come from the soil, growing media or fertilizer regime (Nelson, 1996). Three of these nutrients, known as primary macro nutrients are nitrogen, phosphorus, and potassium, and the ratio of these is what is noted on fertilizer labels (Nelson, 1996).

Soluble salts come from fertilizer, organic matter in the substrate, and dissolved minerals in the irrigation water (Mathers et al., 2007). Soluble salt concentration within the media is most commonly tested by determining the electrical conductivity (EC) of the media in decisiemens per meter ($dS \cdot m^{-1}$). The relationship between the EC of the water (EC_w) and total dissolved salts is the EC_w x 640 = total dissolved salts in $mg \cdot L^{-1}$.

Electrical conductivity (EC) can be measured in a variety of ways. Analytical labs often use the 1:2 dilution method or the saturated media extract (SME) method, while in the greenhouse or nursery, the pour through extraction method is commonly used (Scoggins and van Iersel, 2006). The pour-through extraction method uses distilled water in an amount suitable to leach approximately 50 ml of water into a catchment container and the leachate is then analyzed for EC and pH (Wright, 1986). This method does not allow for complete nutrient analysis in the greenhouse, but rather gives a measurement of the total amount of soluble salts in the leachate. The leachate can be sent to a lab for complete analysis if required. This method has been shown to be repeatable and accurate enough for most grower level analysis and requires no specialized equipment to extract the solution from the medium (Wright, 1986).

Optimal nitrogen (N) rates vary widely by plant species, the media used, and the form of nitrogen applied. Initial nutrient content for young plants and seedlings should be low so that the plants are not damaged by excess salts (Fonteno, 1996). Full strength fertilization should not commence until the young plants are established and actively growing. Once established, Nelson (1996) recommends nitrogen rates of 100 to 260 $mg \cdot L^{-1}$ N for a variety of herbaceous crops on a constant liquid feed program or 240 to 720 $mg \cdot L^{-1}$ N weekly. Other studies also show that for constant liquid feed, nitrogen rates between 100 and

300 mg·L^{-1} N are ideal for a variety of greenhouse crops (Gamrod and Scoggins, 2006; White and Scoggins, 2005).

Plant Growth Regulators

Plant growth regulators (PGRs) are chemicals intended to manipulate plant characteristics. PGRs can be used during propagation to increase seed germination, improve rooting of cuttings, and to trigger growth in tissue cultures (Carey, 2008). In production applications, PGRs may be used to increase or decrease growth rate, chemically pinch plants, induce buds to break dormancy or apical dominance, and to delay flowering (Carey, 2008). Some PGRs are simply artificial plant hormones and are intended to mimic the action of actual hormones found in plants. Others are designed to inhibit the synthesis, reception, or metabolism of hormones, thus negating their effects (Carey, 2008).

Configure® is a PGR from Fine Americas (Walnut Creek, CA) introduced in 2007. Configure's active ingredient, N-(phenylmethyl)-1H-purine-6-amine, also known as benzyladenine or 6-BA is a synthetic cytokinin. Cytokinins are plant hormones responsible for the release of lateral buds from apical dominance and the promotion of cell division and differentiation (Latimer and Whipker, 2010). Plant responses to Configure vary widely by species, variety, growth stage of plant, water and fertilizer management, light, and other cultural influences (Latimer and Whipker, 2010). Recommended application rates for Configure range from 100 mg·L^{-1} for crops such as Christmas Cactus (*Schlumbergera bridgessii* Lem.) up to 5000 mg·L^{-1} for Hostas (*Hosta spp.* Tratt.) (Carey et. al, 2010). Overdosing plants can lead to phytotoxic effects such as leaf yellowing, cupping, changes to morphology, and edge necrosis (Carey et. al, 2010).

Some specific work with Configure has been done on succulent species. A foliar application of Configure at 400 mg·L^{-1} increased offsetting and flowering in *Echeveria setosa*, increased offsets on *Sempervivum* varieties, and increased the number of flower stalks on *Aloe* 'Grassy Lassie' (Carey, 2008).

Augeo™ (OHP, Mainland, PA) is a relatively new PGR using 2,3:4,6-di-o-isopropylidene-2-keto-L, gulonate, commonly known as dikegulac-sodium as its active ingredient. The product information bulletin from OHP claims that Augeo™ "enhances overall structure and appearance by reducing apical dominance and promoting lateral branching" (OHP, 2010). This results in a fuller, more compact plant that may be more appealing to consumers. Augeo™ disrupts cell wall activity, causing a pinching effect on the plant (OHP, 2010). OHP's application rate recommendations range from 400 mg·L^{-1} to 6400 mg·L^{-1} Augeo, depending on plant species and level of regulation desired.

Studies using dikegulac-sodium date as early as the mid-1970s. Azree et al. (1977) showed that dikegulac would inhibit terminal bud development even if applied to only one leaf, and noted that the chemical is quite rapidly translocated to areas of growing tissue. They ultimately found that dikegulac inhibits internode elongation as well as GA-induced DNA synthesis. This indicates that the chemical works counter to gibberellins. The reversal of apical dominance shows that dikegulac also works counter to auxins (Azree, 1977). Hanks and Menhennet (1980) did work on lily hybrids and found that dikegulac at any concentration stopped growth soon after treatment, and prevented the development of flower buds. Nightingale et al. (1985) studied the effects of dikegulac on several Kalanchoe varieties and found that with most varieties, inflorescences were increased at rates up to 2250 mg·L^{-1} Augeo, while plant height and diameter were generally reduced with increasing rates (Nightingale et al., 1985).

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Chapter 2 - The Effect of Potting Media on the Growth of Potted Succulents

Introduction

Container grown succulent plants have increased in popularity and market share over the past several years. Succulents are becoming popular at retail stores in dish gardens (multiple individuals/species in a shallow container), as specimen (high value, individual) plants, as well being made into many specialty items such as living wreaths or walls (Onofrey, 2011). The green roof industry is also growing in the United States, expanding demand for wholesale succulents, such as sedums (*Sedum spp.* L.) at affordable prices (Rowe et al., 2006). Tissue culture has made more varieties available to growers as liners, but the problem remains that many of these plants are slow growers, leading to long crop production cycles (turn times). It may be possible to reduce these production times and increase growers' profits by manipulating certain cultural practices such as irrigation and fertilization regimes, or the media in which the plants are grown.

Growing media serves four functions. It provides water to the plant roots, supplies nutrients, allows for gas exchange to and from the roots, and provides physical support, serving as an anchor for the plant (Fonteno, 1996). A medium's physical and chemical properties can have a profound effect on plant growth and quality (Blythe and Merhaut, 2007). Chemical properties such as pH, electrical conductivity, and cation exchange capacity impact nutrient availability to the plant. Physical properties such as total porosity, bulk density, container capacity and airspace can affect the amount of water available to the plant, as well as the gas exchange ability of the roots (Fonteno and Harden, 2003). The percentages of the components in the media affect both its physical and chemical properties (Fonteno, 1996). Most greenhouse substrates are a mixture of sphagnum peat moss and composted pine bark, with one or more inorganic amendments. These amendments are most commonly perlite and vermiculite, but may also include sand, crushed industrial aggregates (Owen et al., 2007), and expanded shale (Rowe et al., 2006) among other materials such as lime or fertilizer (Graham, 1987). These amendments serve to increase drainage, reduce weight, and alter chemical properties such as pH or CEC (Rowe et al., 2006).

Conventional wisdom indicates that succulent plants will only thrive in well-drained potting media. Evans (1995) states that a way to ensure healthy growth is to fill the pot with fast-draining soil. Both Evans (1995) and Graham (1987) recommend sand as an essential component of media for succulents. Graham (1987) states that the ideal mixture for succulents should have a neutral pH, and be 'porous, free-draining, and loose to the touch.' There are many commercially available substrates with these properties. The purpose of this experiment is to determine which media components and combinations are best for rapidly producing quality potted succulents.

Materials and Methods

Plant material. Ten species of ornamental succulents were studied over the course of two groups. *Agave* L. 'Blue Glow' is a Proven Selections® hybrid. Proven Winners calls it a 'magnificent hybrid with red-tinged leaves'. The rosettes of foliage have a distinctly blue cast (Proven Winners, 2012). *Agave geminiflora* (Tagliabue) 'Rasta Man' is a selection of *A. geminiflora* marketed by Proven Winners. It is a 'pincushion' type *Agave* from the subgenus Littaea, group Filiferae. *Senecio cephalophorus* (Compton)'Blazin' Glory' is a Proven Winners selection of *S. cephalophorus* which is native to the Northern Cape Province of the Republic of South Africa. It displays soft, bluish green foliage and large, numerous orange flowers. *Dyckia* (Dyck)'Burgundy Ice' is a *Dyckia* hybrid by Kelly Griffin. *Dyckia* is one of the most primitive Bromeliad genera, as well as one of the most cold-tolerant. *D.* 'Burgundy Ice' is named for its deep purple foliage. Flowers are borne in spikes and have colored bracts (Sajeva and Costanzo, 2000). *Aeonium* (L.) 'Kiwi' produces rosettes of spoon–shaped leaves on short stems are primarily green with yellow and pink edges. Light yellow flowers appear in late summer (Proven Winners, 2012). *Crassula coccinea* (L.) 'Campfire'is a branching succulent with light green propeller shaped leaves that mature to a bright red color. Small, white flowers are dispersed along the stem (San Marcos Growers, 2011). *Echeveria* (De Candolle) 'Afterglow' grows a large rosette of fleshy leaves covered with a lavender colored powder; especially in ideal sun (Proven Winners, 2012). Large spikes of orange flowers emerge from below leaves or sometimes as terminal florescence (Proven Winners, 2012). *Echeveria* 'Violet Queen' has rosette forming gray foliage, 10 to 13 cm high, with each rosette 15 to 20 cm across. *Aloe* (L.) 'Fire Ranch' has fleshy, strap-like green leaves borne in rosettes. *A.* 'Fire Ranch' bears numerous red-orange flowers on multiple spikes. *Aloe* 'Grassy Lassie' produces deep green, narrow, grass-like leaves with bright orange flowers. In full sun, foliage becomes a deep bronze (Proven Winners, 2012). *Aloe variegata* (L.) 'Gator' has stem-less rosettes up to 25 cm tall. Leaves are green to brownish green with white spots arranged in bands. Plants bear pink flowers on a spike up to 30 cm tall (Proven Winners, 2012).

Substrate treatments, cultural practices and data collection. Studies were conducted on benches in a double-polyethylene covered greenhouse on the Virginia Tech campus in Blacksburg, VA (lat. 37°13' N, long. 80°25' W). Daytime maximum temperature was set at 27°C and nighttime minimum temperature was set at 18°C. The species studied were divided into two groups, grown consecutively due to space constraints. All plants received a preventative fungicide drench consisting of a tank mix of 0.57 $g\cdot L^{-1}$ Banrot (Etridiazole 15%, Thiophanate-methyl 25%) - (Scotts, Marysville, OH) and 0.1 $mL\cdot L^{-1}$ Subdue Maxx® (Mefenoxam 22%) - (Syngenta Crop Protection LLC., Greensboro, NC) the day after they were potted. Height, width, and numbers of offsets (new rosettes that can be used for propagation) or leaders (primary branches with secondary lateral branches) and branches (no secondary branching) were measured and recorded at the time of potting and approximately every two weeks thereafter. Plants were harvested when deemed market ready (Table 1), defined as when shoot growth of about half of the individuals in the study reached or was approaching the edges of the pots. At harvest, shoots were separated from the roots at the soil line, placed in paper bags, and oven dried for one week at 65°C. The dried shoot weights were then recorded.

Group one. On November 17, 2010 four species of succulents were received from Euro American Propagators (Bonsall, CA). *Aloe* 'Fire Ranch' and *Echeveria* 'Afterglow' were received in thirty two cell

(199 ml/cell) trays and *Agave* 'Blue Glow' and *Senecio* 'Blazin' Glory' were received in 84 cell (45 ml/cell) trays. *Echeveria* was potted into 2.77 L round pots, all other species were potted into square 946 ml pots.

Each species was placed into a completely randomized design consisting of five treatments, each with six replications. Treatments were : peat-lite [100% Pro-Mix BX Mycorrhizae (Premier Tech Horticulture, Quakertown, PA)], bark/peat [100% Fafard 52 Mix (Conrad Fafard, Inc., Agawam, MA)], whole-tree [100% Fafard Timba-Tec TT600 (Conrad Fafard, Inc.)], bark [100% Composted Pine Bark (Riverbend Nursery, Riner, VA)] and bark/permatil [80% composted pine bark/20% Permatil v/v (Carolina Stalite Company, Salisbury, NC)]. All plants within the study were irrigated to container capacity with a constant liquid feed of Jack's Cal-Mag 15-5-15 (15N -2.2P-12.5K) (J.R. Peter's, Allentown, PA) at 100 $mg \cdot L^{-1}$ N when the average volumetric moisture content of three plants per treatment fell below 20% as measured by a Waterscout SM 100 soil moisture sensor (Spectrum Technologies, Plainfield, IL). Average daily light integral (DLI) for group 1 was 19.5 $mol \cdot m^{-2} \cdot d^{-1}$.

Group two: On June 29, 2011 five species of succulents were received from Euro American Propagators (Bonsall, CA). *Aloe* 'Gator'was received in a 96 cell (37 ml/cell) tray and potted into 76- ml round azalea pots. *Dyckia* 'Burgundy Ice' was received in an 84 cell (45 ml/cell) tray and potted into the same azalea pots. *Agave* 'Rasta Man' and *Aloe* 'Grassy Lassie' were received in 96 cell trays and potted into 1.9-L round Teku (Poppelmann Plastics USA LLC, Claremont, NC) pots. *Aeonium* 'Kiwi' was received in 50 cell (111 ml/cell) trays and potted into the Teku pots. *Crassula coccinea* 'Campfire' was received in 50 cell trays on July 20, 2011 and potted into the 1.9-L Teku pots. *Echeveria* 'Violet Queen' was received on August 10, 2011 and potted into the 766-ml azalea pots.

Each species was placed into a completely randomized design consisting of four treatments, each with six replications. Treatments were: peat-lite, bark/peat, whole-tree, and bark. Bark/Permatil was dropped from the second group due to overall poor performance of plants in the first group. All plants were irrigated to container capacity with a constant liquid feed of Jack' All Purpose 20-10-20 (20N-4.4P-16.6K) at 150 $mg \cdot L^{-1}$ N when the volumetric moisture content fell below 25% as measured by a Waterscout SM 100 soil moisture sensor. The watering threshold was adjusted due to experiences with group one. Average DLI for group two was 23.5 $mol \cdot m^{-2} \cdot d^{-1}$.

Substrate physical property measurements. The physical properties of the media, total porosity, container capacity, air space, and bulk density, were tested and recorded for each of the substrates used with the North Carolina State Porometer, following the procedures laid out in Fonteno and Harden (2003).

Substrate pH and electrical conductivity (EC) measurements. Substrate pH and EC was tested at the time of potting and at harvest using the pour thru extraction procedure (Wright, 1986). Measurements were taken with a Hanna HI 9811 portable pH – EC – TDS meter (Hanna Instruments, Smithfield, RI).

Statistical analyses. Data were analyzed by analysis of variance using JMP9 (SAS Institute, Inc., Cary, NC). Comparisons of means among treatments were conducted using Tukey's honest significant difference (HSD) test at $P < 0.05$.

Results

Media affected the growth parameters measured of almost all taxa studied. Only one of the eleven species tested, *Agave* 'Rasta Man,' showed no significant differences among any of the characteristics measured. In group 1, *Echeveria* 'Afterglow' and *Senecio* 'Blazin' Glory' were the first to finish, and in group 2 *Crassula.* 'Campfire' was the first to finish (Table 2.1). *Agave* 'Blue Glow' and *Aloe* 'Fire Ranch were the slowest plants to reach market readiness in group 1, and in group 2, *Aloe* 'Gator was the slowest. Offset production was not affected by media type (data not shown).

The peat-lite substrate had the highest total porosity, and lowest bulk density of the substrates used(Table 2.2). The bark/Permatil substrate had the lowest total porosity and highest bulk density. Bark/peat had the highest container capacity and least amount of airspace while the bark/Permatil had the lowest container capacity and the bark had the most airspace. There were no noticeable trends among the pH of the substrates, but the bark and bark/Permatil exhibited reduced EC measurements when compared to the other substrates (Table 2.3).

In group 1, media affected the shoot dry weights of all species except *Echeveria* 'Afterglow' (Table 2.4), with the peat-lite and whole tree media generally producing greater mass. *Agave* 'Blue Glow' grew plants of the greatest mass when grown in whole tree. Peat-lite produced the heaviest *Aloe* 'Fire Ranch' as well as *Senecio* 'Blazin Glory.' Bark/permatil displayed the lowest plant dry weight across all species (Table 2.4). In group 2, *Agave* 'Rasta Man' and *Aloe'* 'Grassy Lassie' did not differ in dry weight when grown in different media (Table 2.5). *Aeonium* 'Kiwi,' *Agave* 'Rasta Man,' and *Crassula* 'Campfire' all had the highest shoot dry weight when grown in peat-lite or whole tree. *Dyckia* 'Burgundy Ice' was similar in dry weight in all media except bark, which produced plants of lesser mass (Table 2.5) .

In group 1, plant height of *Agave* 'Blue Glow' and *Echeveria* 'Afterglow' was not affected by media (Table 2.6). *Aloe* 'Fire Ranch' was the widest when grown in grown in peat-lite, bark/peat, or whole tree. *Senecio* 'Blazin Glory' grew tallest when potted into whole tree. All taxa were shortest when grown in bark/permatil. In group 2, *Aeonium* 'Kiwi,' *Agave* 'Rasta Man,' *Aloe* 'Grassy Lassie,' and *Aloe* 'Gator' were not of different heights when grown in different media. *Crassula* 'Campfire' was tallest when grown in bark. *Dyckia* 'Burgundy Ice' was tallest when grown in any media except bark. *Echeveria* 'Violet Queen' was tallest when grow in whole tree or bark/peat (Table 2.6).

In group 1, media showed no effect on the width of *Agave* 'Blue Glow' or *Echeveria* 'Afterglow' (Table 2.7) The width of *Aloe* 'Fire Ranch' was similar across all treatments except bark/permatil, which produced the plants with the least width. *Senecio* 'Blazin' Glory' displayed the widest plants when grown in peat-lite or whole tree. In group 2, the width of *Agave* 'Rasta Man' and *Aloe* 'Gator' was not affected by media. All species produced the narrowest plants when grown in bark. *Aeonium* 'Kiwi' was not different in any media except bark. *Aloe* 'Gator' also showed no differences in width except for plants grown in bark. The same is true for *Crassula* 'Campfire'. Both *Dyckia* 'Burgundy Ice' and *Echeveria* 'Violet Queen' grew the widest in bark/peat or whole tree (Table 2.7).

Discussion

Across both experiments and all species, the composted bark and bark/permatil substrates consistently performed the worst with generally lower shoot dry weights and slower growth. Porometer tests indicated that the bark based media had overall lower porosity and higher bulk density than the other media tested, and the addition of permatil to the bark further reduced porosity and increased bulk density. The peat-lite and whole tree substrates had some of the highest porosity and lowest bulk densities and tended to perform best, producing larger plants and better filled pots (Figure 2.1). The results of these experiments indicate that high porosity and low bulk density are the most desirable physical properties for a medium in which to grow succulents. This is consistent with Graham's (1987) recommendation that it should be "porous, and loose to the touch", but may be contrary to Evan's (1995) statement that 'free draining' is essential.

There has been very little scientific research on the best media for potted ornamental succulents. Most of the research that has been done on substrates for growing succulents has been in the green roof industry (Rowe et al., 2006), which has different requirements than the greenhouse industry. Rowe et al. (2006) looked at the potential of heat-expanded slate (Permatil) as a green roof substrate and found that higher levels of slate in the substrate generally reduced growth in *Sedum.* He suggests that water availability is a key factor. This corresponds with our findings of the bark/permatil media generally yielding the lowest shoot weights of the substrates tested. Further, our porometer tests show that the addition of the expanded slate to bark further reduces airspace, container capacity, ant total porosity while increasing bulk density. This leads to less water available to the plant.

It is common in the literature to see recommended that succulents be grown in ‘well drained,’ or ‘fast draining’ soil. This is never really defined, but seems to indicate that substrates should have low water holding capacity or a high percolation rate. Graham (1987) states that the substrate should be “porous, free-draining, and loose to the touch.” This corresponds more to our findings in that substrates with greater total porosity and lower bulk density produced large plants (Figure 2.1, 2.2). Graham (1987) also states that succulent growth can be inhibited if the media settles too much or is packed too tightly, retaining too much moisture and excluding air. This also coincides with our findings that substrates with lower bulk density perform better.

It should also be noted that the bark and bark/permatil substrates had lower EC values than any of the other substrates. This may be a function of their lower porosity and water holding ability. Cation exchange capacity was not tested. pH was fairly consistent among all the substrates, with values around 6.0. Graham (1987) states that pH should ideally be neutral, further investigation is required to determine the effect of pH on growth.

As mentioned before, the chemical and physical properties of growing media can have a significant impact on plant growth. This study demonstrated that potted ornamental succulents prefer a substrate with high porosity, container capacity, and airspace, as well as low bulk density. This response is somewhat species specific. For example, *A.* ‘Fire Ranch’ grew widest in bark media, thus filling the pot faster even though its shoot dry weight was lowest in the bark. Based on the similar performances of all but the bark and bark/permatil media, it may be difficult to make a broad recommendation of a substrate for growing all succulent plants.

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Table 2.1. Weeks to harvest. Taxa were harvested when they were deemed 'market ready,' defined as when shoot growth of about half of the individuals in the study reached or was approaching the edges of the pots.

Species	Weeks To Harvest
Group 1	
Agave ‘Blue Glow’	20
Aloe ‘Fire Ranch’	20
Echeveria ‘Afterglow’	10
Senecio ‘Blazin’ Glory’	10
Group 2	
Aeonium ‘Kiwi’	11
Agave ‘Rasta Man’	17
Aloe ‘Gator’	21
Aloe ‘Grassy Lassie’	12
Crassula ‘Campfire’	6
Dyckia ‘Burgundy Ice’	12
Echeveria ‘Violet Queen’	12

Table 2.2 Physical properties of substrates in study, determined using the North Carolina State University Porometer (Fonteno and Harden, 2003).

Substrate	Total Porosity (%)	Container Capacity (%)	Air Space (%)	Bulk Density (g/cm^3)
Bark/Peat	80.4	67.6	18.8	0.18
Peat-Lite	87.4	61.6	19.8	0.11
Whole-tree	85.7	61.7	23.9	0.16
Bark	83.7	59.4	24.5	0.20
Bark / Permatil	75.7	53.4	22.2	0.34

Table 2.3. pH and EC values. pH and EC data was collected at potting and harvest using the pour-thru extraction procedure (Wright, 1986). Three individuals per taxa per treatment were sampled and the results averaged.

	Peat Lite				Bark/Peat				Whole-Tree				Bark				Bark/Permatil			
	pH		EC($ds \cdot m^{-1}$)		pH		EC($ds \cdot m^{-1}$)		pH		EC($ds \cdot m^{-1}$)		pH		EC($ds \cdot m^{-1}$)		pH		EC($ds \cdot m^{-1}$)	
	Begin	End	Begin	End	Begin	End	Begin	End	Begin	End	Begin	End	Begin	End	Begin	End	Begin	End	Begin	End
Agave 'Blue Glow'	6.2	5.9	1.15	2.12	6.5	5.9	1.55	2.72	5.8	5.6	0.93	2.05	6.4	6.1	0.56	1.28	6.4	6.3	0.61	0.99
Aloe 'Fire Ranch'	6.2	5.9	1.1	2.07	6.5	5.8	1.34	2.38	5.8	5.6	0.95	1.73	6.3	5.8	0.6	1.02	6.3	6.2	0.62	0.83
Echeveria. 'Afterglow'	5.9	6.3	1.38	1.34	6.4	6.5	1.79	1.67	5.6	6.1	1.42	1.05	5.9	6.8	0.99	0.63	6.1	6.7	0.66	0.61
Senecio 'Blazin' Glory'	6.1	6.3	1.38	1.19	6.6	6.6	1.3	1.4	5.6	5.8	1.33	1.01	6.3	6.3	0.71	0.75	6.4	6.7	0.81	0.68
Aeonium 'Kiwi'	5.9	5.5	1.88	2.24	5.7	5.3	1.78	1.88	5.7	5.1	1.31	1.49	5.3	5.5	0.54	0.93	x	x	x	x
Agave 'Rasta Man'	5.8	5.1	2.05	3.31	6.4	5.3	1.7	2.62	5.9	4.9	1.6	2.74	5.5	5.7	0.64	0.49	x	x	x	x
Aloe 'Gator'	6.0	5.5	2.51	2.72	6.1	5.7	1.51	2.05	5.6	5.1	1.41	1.24	5.7	5.4	0.64	0.6	x	x	x	x
Aloe 'Grassy Lassie'	5.9	5.7	2.58	2.4	6.2	5.8	2.03	2.27	5.5	5.5	1.26	1.62	5.8	5.3	0.61	1.12	x	x	x	x
Crassula 'Campfire'	6.0	5.6	2.26	1.03	6.2	5.5	1.76	1.21	5.6	5.3	1.31	0.63	5.7	5.7	0.62	0.54	x	x	x	x
Dyckia 'Burgundy Ice'	6.0	6.0	2.34	2.61	5.9	5.6	1.58	1.73	6	5.7	1.22	1.75	5.7	5.7	0.76	0.8	x	x	x	x
Echeveria. 'Violet Queen'	6.1	6.0	2.41	1.83	6	5.9	1.67	0.63	6.2	5.7	1.18	0.7	5.9	6.2	0.68	0.28	x	x	x	x

Table 2.4. Means of shoot dry weight (g) for plants in group 1, grown in five different substrates. Data analyzed using Tukey's honest significant difference, $P \leq 0.05$, n = 6. Means followed by the same letter are not significantly different at $P \leq 0.05$1

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	Shoot dry weight (g)			
Media	*Agave* 'Blue Glow'	*Aloe* 'Fire Ranch'	*Echeveria* 'Afterglow'	*Senecio* 'Blazin' Glory'
Bark	1.98ab	2.94c	11.6	1.22c
Bark/Permatil	1.74b	2.09c	10.9	0.99c
Bark/Peat	2.11ab	2.95b	10.8	2.06b
Peat – Lite	2.27ab	3.58a	11.7	2.94a
Whole Tree	2.49a	3.11b	13.3	2.57ab
P-Value	0.082	<0.0001	0.7205	<0.0001
HSD	0.27	0.19	1.97	0.28

Table 2.5. Means of shoot dry weights (g) for plants in group 2, grown in four different substrates. Data analyzed using Tukey's honest significant difference, $P \leq 0.05$, $n = 6$. Means followed by the same letter are not significantly different at $P \leq 0.05$.

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	Shoot dry weight (g)					
Media	*Aeonium* 'Kiwi'	*Agave* 'Rasta Man'	*Aloe* 'Gator'	*Aloe* 'Grassy Lassie'	*Crassula* 'Campfire'	*Dyckia* 'Burgundy Ice'
Bark	4.29b	3.54	0.78b	1.94	4.53c	1.49b
Bark/Peat	5.47ab	3.86	1.36ab	2.96	6.87b	2.69a
Peat - Lite	6.04a	4.02	1.56a	2.91	9.93a	2.38a
Whole Tree	6.17a	3.68	1.57a	2.89	8.97ab	2.49a
P-Value	0.0065	0.7616	0.0291	0.2111	<0.0001	<0.0001
HSD	0.51	0.48	0.27	0.54	0.76	0.19

Table 2.6. Means of shoot heights (cm) at potting and at harvest. Data analyzed using Tukey's honest significant difference, P≤0.05, n=6. Means of end point heights followed by the same letter in a row are not significantly different at P≤0.05.

	Plant height										P-Value	HSD
	Peat-Lite		Bark/Peat		Whole tree		Bark		Bark/Perm			
	Start	End	Start	End	Start	End	Start	End	Start	End		
A.'Blue Glow'	1.3	3.6	1.5	3.7	1.2	3.3	1.7	3.2	1.5	3.5	0.7496	0.41
A. 'Fire Ranch'	2.1	6.1a	1.1	5.8a	2.1	5.6a	2.2	4.5b	2.2	4.5b	<0.0001	0.44
E. 'Afterglow'	8.1	11.3abc	8.8	12.5ab	9.1	13.5a	7.8	10.2bc	8.1	9.8c	0.0206	1.17
S. 'Blazin Glory'	2.8	7.7b	3.0	7.3b	3.2	9.0a	2.8	3.5c	2.6	4.1c	<0.0001	0.59
Group 2												
A. 'Kiwi'	4.6	8.8	5.5	9.6	5.1	9.8	5.8	8.8	x	x	0.4338	0.77
A. 'Rasta Man'	5.5	10.2	6.1	10.7	5.8	10.0	7.1	10.3	x	x	0.6504	0.54
A. 'Gator'	1.0	3.6	1.0	3.5	1.3	3.6	1.8	2.5	x	x	0.1587	0.57
A. 'Grassy Lassie'	6.0	22.3	7.0	22.7	6.6	23.5	7.0	18.7	x	x	0.0865	0.58
C. 'Campfire	15.0	14.2b	14.7	15.3b	15.0	12.7b	14.7	24.5a	x	x	0.0066	1.9
D. 'Burgundy Ice'	2.3	7.8a	2.5	8.6a	2.1	7.0ab	2.5	5.6b	x	x	0.0037	0.72
E. 'Violet Queen'	2.0	3.0b	2.3	4.0a	2.0	3.6a	2.0	2.6b	x	x	0.0004	.55

Table 2.7. Means of shoot average widths (cm) at potting and at harvest. Data analyzed using Tukey's honest significant difference, P≤0.05, n=6. Means of end point widths followed by the same letter in a row are not significantly different at P≤0.05.2

	Peat-Lite		Bark/Peat		Whole tree		Bark		Bark/Perm		P-Value (End)	HSD
	Average Width (cm)											
Group 1	Start	End	Start	End	Start	End	Start	End	Start	End		
A.'Blue Glow'	6.1	8.8ab	6.4	9.19a	6.9	9.1a	6.1	7.4c	6.4	7.8bc	0.0083	0.54
A. 'Fire Ranch'	9.1	14.7a	8.3	14.8a	8.9	14.5a	8.3	13.1a	8.3	10.7b	<0.0001	0.86
E. 'Afterglow'	22.0	27.4ab	21.2	30.3a	20.7	26.7ab	19.3	25.7bc	20.6	22.6c	0.0042	1.76
S. 'Blazin Glory'	6.8	16.3a	7.1	14.3b	7.1	16.5a	6.7	7.31c	6.8	7.0c	<0.0001	0.58
Group 2												
A. 'Kiwi'	8.9	13.9a	8.8	13.2ab	9.1	14.0a	8.4	12.0b	x	x	0.0147	0.62
A. 'Rasta Man'	14.1	19.4	12.8	21.1	12.8	19.5	14.2	19.4	x	x	0.1533	0.94
A. 'Gator'	2.7	5.9a	2.5	5.5ab	2.6	5.6a	2.8	3.9b	x	x	0.0107	1.13
A. 'Grassy Lassie'	10.6	27.2	9.0	31.9	9.1	33.3	10.8	20.8	x	x	0.1127	0.53
C. 'Campfire	13.6	23.0a	13.3	22.5a	12.8	23.0a	13.3	19.9b	x	x	0.0002	0.50
D. 'Burguny Ice'	7.7	13.4b	7.7	15.5a	7.6	14.7ab	7.3	11.4c	x	x	<0.0001	1.26
E. 'Violet Queen'	6.8	7.3b	6.7	8.5a	6.8	8.3a	6.4	6.8b	x	x	<0.0001	0.24

Figure 2. 1. Media total porosity (%) vs. shoot dry weight (g) of Aloe 'Fire Ranch' grown in five media of differing total porosity (See Table 2.2)

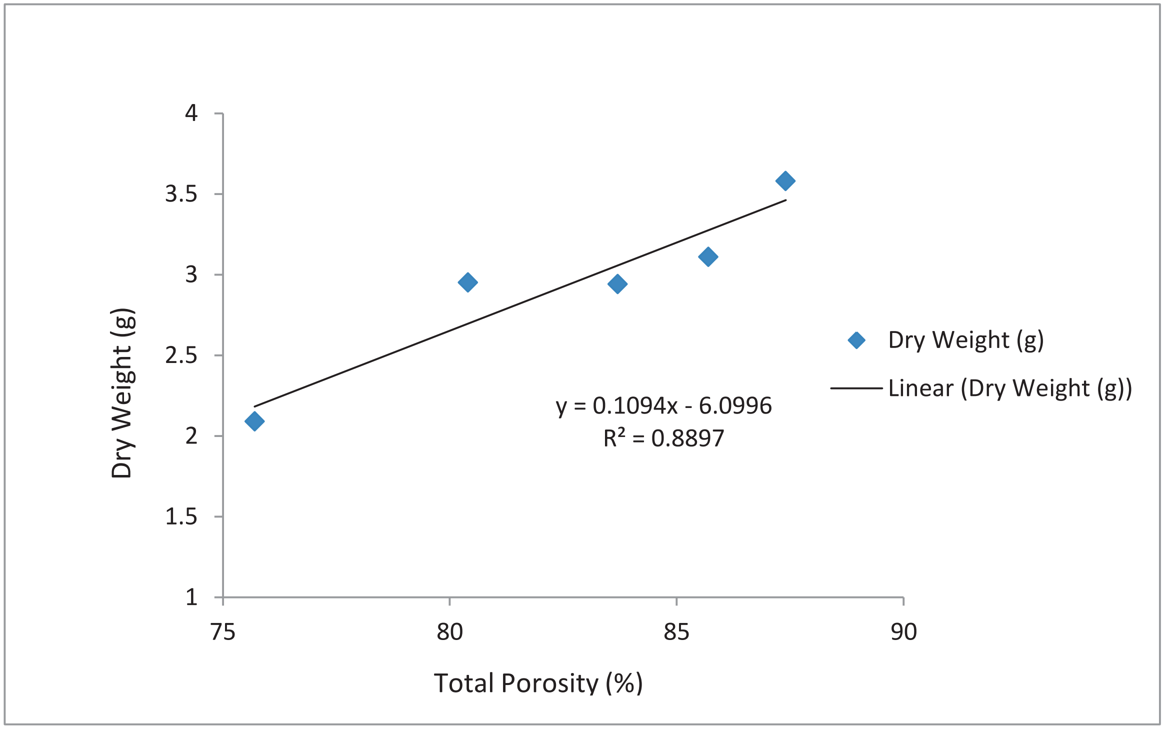
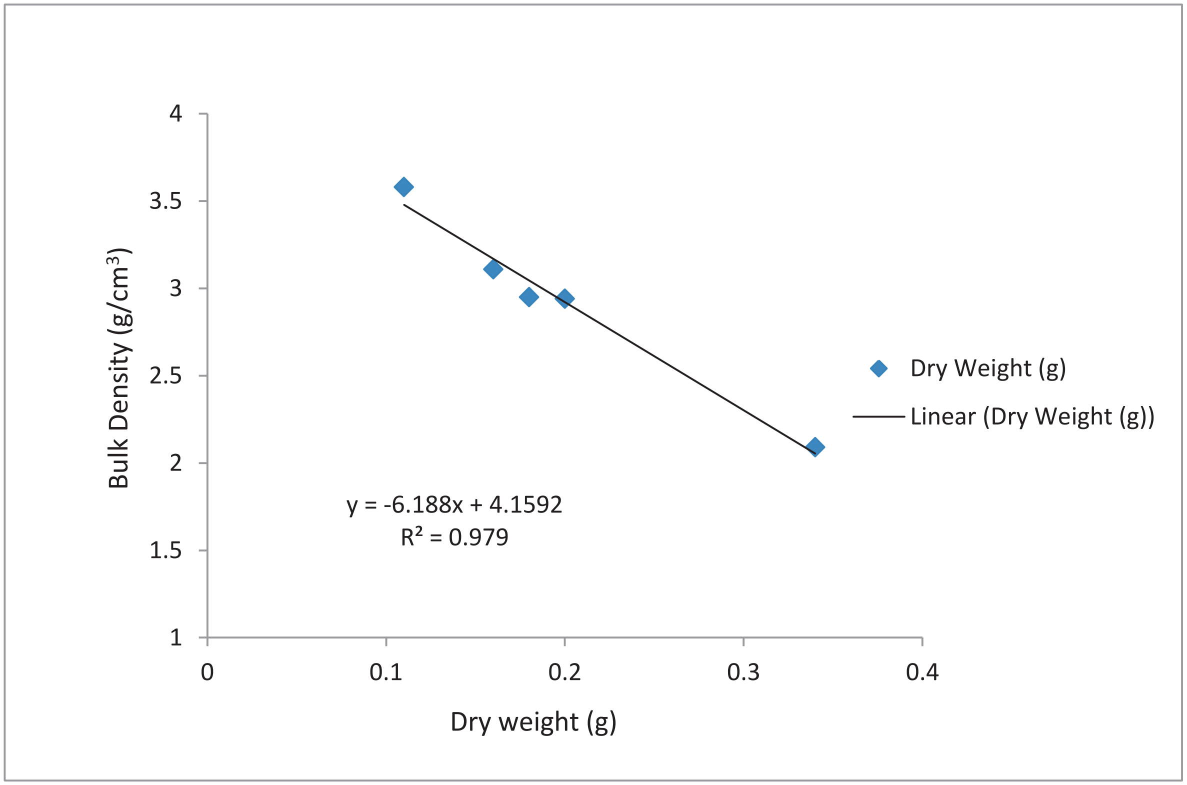


Figure 2. 2. Bulk density vs. shoot dry weight (g) of Aloe 'Fire Ranch' grown in five media of differing bulk densities. (See Table 2.2)



Chapter 3 - The Effect of Soil Volumetric Moisture Content on Growth of Potted Succulents

Introduction

Container grown succulent plants have been increasing in popularity and market share over the past several years. Succulents are becoming popular at retail stores in dish gardens, as specimen plants, as well being made into many specialty items such as living wreaths or walls (Onofrey, 2011). The green roof industry is also exploding, expanding demand for wholesale succulents, such as sedums (*Sedum spp.* L.) at affordable prices. Tissue culture has made more varieties more available to growers as liners, but the problem remains that many of these plants are slow growers, leading to long production times. It may be possible to reduce these production times and increase growers' profits by manipulating certain cultural practices such as irrigation and fertilization regimes, or the media in which the plants are grown.

Managing water resources is one of the most important challenges in production (Van Iersel et al., 2010). Therefore knowledge about plant tolerance to moisture stress is important (Bousselot et al., 2011). Irrigation management is important in ornamental crop production for reducing nutrient and pesticide laden runoff, producing high quality plants, and reducing overall production costs (Van Iersel et al., 2010). Irrigation management entails controlling the moisture content of the root zone and there are several methods for determining when to irrigate. Some of these methods include look and feel, gravimetric, timers, sensors, and models (Lieth, 1996).

While it has been shown that there are optimal soil moisture levels for the growth of ornamental crops, imposition of specific levels has proved difficult (Kiehl et al., 1992). Optimal levels vary based on the crop being grown, the media used and other factors. Plant growth is generally inhibited at moisture levels below 15%, but can vary widely by species (van Iersel, et al., 2010). Petunias (*Petunia spp.* Juss.), for example exhibit drought stress at moisture levels below 25% (Van Iersel et al., 2010) but moisture contents between 24% and 34% are ideal for optimal growth in other herbaceous crops such as snapdragon (*Antirrhinum spp.* L.) (Kiehl et al., 1992). Succulents, such as sedums, generally retain moisture in the substrate longer than other herbaceous plants, and can tolerate lower substrate moisture contents before indicating stress (Bousselot et al., 2011).

Materials and Methods

Plant material. Thirteen taxa of ornamental succulents were studied over the course of two experiments. *Agave* L. 'Blue Glow' is a Proven Selections® hybrid. Proven Winners calls it a 'magnificent hybrid with red-tinged leaves'. The rosettes of foliage have a distinctly blue cast (Proven Winners, 2012). *Agave geminiflora* (Tagliabue) 'Rasta Man' is a selection of *A. geminiflora* marketed by Proven Winners. It is a 'pincushion' type *Agave* from the subgenus Littaea, group Filiferae. *Senecio cephalophorus* (Compton)'Blazin' Glory' is a Proven Winners selection of *S. cephalophorus* which is native to the Northern Cape Province of the Republic of South Africa. It displays soft, bluish green foliage and large, numerous orange flowers. *Dyckia* (Dyck) 'Burgundy Ice' is a hybrid by Kelly Griffin. *Dyckia* is one of the most primitive Bromeliad genera, as well as one of the most cold tolerant. *D.* 'Burgundy Ice' is named for its deep purple foliage. Flowers are borne in spikes and have colored bracts (Sajeva and Costanzo, 2000). *Aeonium* (L.) 'Kiwi' displays rosettes of spoon–shaped leaves on short stems that are primarily green with yellow and pink edges. Light yellow flowers appear in late summer (Proven Winners, 2012). *Crassula coccinea* (L.) 'Campfire' is a branching succulent with light green propeller shaped leaves that mature to a bright red color (San Marcos Growers, 2011). Small, white flowers are dispersed along the stem. *Echeveria* (De Candolle) 'Afterglow' grows in a large rosette of fleshy leaves covered with a lavender colored powder, especially in ideal sun (Proven Winners, 2012). Large spikes of orange flowers emerge from below leaves or sometimes as terminal florescence. *Echeveria* 'Violet Queen' forms rosettes of gray foliage that curls up at the tips, 100 to 125 cm high, with each rosette 150 to 200 cm across (San Marcos Growers, 2011). *Aloe* (L.) 'Fire Ranch' produces fleshy, strap-like green leaves borne in rosettes, and bears numerous red-orange flowers on multiple spikes. *Aloe* 'Grassy Lassie' displays deep green, narrow, grass-like leaves with bright orange flowers. In full sun, the foliage becomes a deep bronze (Proven Winners, 2012). *Aloe variegata* (L.) 'Gator' forms stem less rosettes up to 25 cm tall. Leaves are green to brownish green with white spots arranged in bands. *A.* 'Gator' bears pink flowers on a spike up to 30 cm tall. *Aeonium arboretum* (L.) 'Zwartkop' is an upright growing plant with a fleshy, almost woody stem and rosettes of dark burgundy or purple foliage. Yellow, star shaped flowers form in long clusters from the center of rosettes on mature plants (San Marcos Growers, 2011). *Kalanchoe thyrsifolia* (Harvey) 'Flapjacks' produces fleshy, paddle-like leaves that form rosettes in the shape of a clamshell. Fragrant, powdery white flowers are borne on a spike in early spring. Leaves may be bright green to deep red, depending on light and moisture levels (Proven Winners, 2012).

Cultural practices and data collection. Studies were conducted on benches in a double-polyethylene covered greenhouse on the Virginia Tech campus in Blacksburg, VA (lat. 37°13' N, long. 80°25' W). Daytime maximum temperature was set at 27°C and nighttime minimum temperature was set at 18°C. The species studied were divided into two groups, grown consecutively due to space constraints. Both groups were grown in Fafard 52 Mix (Conrad Fafard, Inc., Agawam, MA). All plants received a preventative fungicide drench consisting of a tank mix of 0.57 $g \cdot L^{-1}$ Banrot (Etridiazole 15%, Thiophanate 25%) - (Scotts, Marysville, OH) and 0.1 $mL \cdot L^{-1}$ Subdue Maxx® (Mefenoxam 22%) - (Syngenta Crop Protection LLC., Greensboro, NC) the day after they were potted. Height, width, and numbers of offsets (new rosettes that can be used for propagation) or leaders (primary branches with secondary lateral branches) and branches (no secondary branching) were measured and recorded at the time of potting and approximately every two weeks thereafter. Plants were harvested when deemed market ready (Table 1). Market ready was defined as when shoot growth reached or was approaching the edges of the pots. At harvest, shoots were separated from the roots at the soil line, placed in paper bags, and oven dried for one week at 65°C. The dried shoot weights were then recorded.

Group one. On November 17, 2010 five species of succulents were received from Euro American Propagators (Bonsall, CA). *Aeonium* 'Zwartkop,' *Aloe* 'Fire Ranch,' and *Echeveria* 'Afterglow' were received in 32 cell (199 ml/cell) trays and *Agave* 'Blue Glow' and *Senecio* 'Blazin' Glory' were received in 84 cell (45 ml/cell) trays. *Aeonium* 'Zwartkop,' and *Echeveria* 'Afterglow' were potted into 2.77-L round pots, all other species were potted into square 946-ml pots. *K.* 'Flapjacks' was received on March 16, 2011 and potted into 2.77-L round pots.

Each species was placed into a completely randomized design consisting of three treatments, each with six reps. The treatments were: low (10% volumetric moisture), medium (20% volumetric moisture), and high (30% volumetric moisture). Moisture measurements were taken daily using a Waterscout SM 100 soil moisture sensor (Spectrum Technologies, Plainfield, IL) according to manufacturer's direction. All plants were watered to container capacity with a constant liquid feed of Jack's Cal-Mag 15-5-15 (15N - 2.2P-12.5K) (J.R. Peter's, Allentown, PA) at 100 mg/L^{-1} N when the volumetric moisture content fell below the designated thresholds. Average daily light integral for group 1 was 19.5 $mol \cdot m^{-2} \cdot d^{-1}$.

Group two: On June 29, 2011 five species of succulents were received from Euro American Propagators. *Aloe* 'Gator' was received in a 96 cell (37 ml/cell) tray and potted into 766-ml round azalea pots. *Dyckia* 'Burgundy Ice' was received in an 84 cell (45 ml/cell) tray and potted into the same. *Agave* 'Rasta Man' and *Aloe* 'Grassy Lassie' were received in 96 cell trays and potted into 1.9-L round Teku (Poppelmann Plastics USA LLC, Claremont, NC) pots. *Aeonium* 'Kiwi' was received in 50 cell (111-ml/cell) trays and potted into the same. *Crassula coccinea* 'Campfire' was received in 50 cell trays on July 20, 2011 and potted into the 1.9-LTeku pots. *Echeveria* 'Violet Queen' was received in 96 cell trays on August 10, 2011 and potted into the 766-ml azalea pots.

Each species was placed into a completely randomized design consisting of three treatments, each with six reps. The treatments were: low (15% volumetric moisture), medium (25% volumetric moisture), and high (35% volumetric moisture). Moisture measurements were taken daily using a Waterscout SM 100 soil moisture sensor. All plants were watered to container capacity with a constant liquid feed of Jack's All Purpose 20-10-20 (20N-4.4P-16.6K) at 150 mg/L^{-1} N when the volumetric moisture content fell below the designated thresholds. Average DLI for group 2 was 23.5 $mol \cdot m^{-2} \cdot d^{-1}$. In addition to the parameters measured in group one, fresh shoot weights were also recorded at the time of harvest for all group 2 plants as a precaution against drier malfunction.

Substrate pH and electrical conductivity measurements. Substrate pH and EC were tested on all crops at the time of potting and at harvest using the pour thru extraction procedure (Wright, 1986). Measurements were taken with an HI 9811 portable pH – EC – TDS meter (Hanna Instruments, Smithfield, RI).

Statistical analyses. Data were analyzed by analysis of variance using JMP9 (SAS Institute, Inc., Cary, NC). Comparison of means among treatments were conducted using Tukey's honest significant difference (HSD) test at $P < 0.05$.

Results

Of the thirteen succulent species evaluated, three species (*Echeveria* 'Afterglow,' *Dyckia* 'Burgundy Ice,' and *Echeveria* 'Violet Queen') were not affected by soil moisture content in any of the measured parameters. None of the crops studied showed any differences in offset production at any volumetric soil moisture treatment (data not presented). For group one, *Echeveria* 'Afterglow' and *Senecio* 'Blazin' Glory' had the shortest crop production cycles, while *Aloe* 'Fire Ranch,' *Aeonium* 'Zwartkop', and *Agave* 'Blue Glow' took the most amount of time to reach market readiness (Table 3.1). In group two, *Crassula* 'Campfire' was the fastest to finish while *Aloe* 'Gator' was the slowest. The pH and EC measurements exhibited no discernible trends other than the pH at harvest was generally lower than the pH at potting (Table 2).

In group 1, volumetric soil moisture (VMS) affected the shoot dry weight of only *Senecio* 'Blazin' Glory,' with the high VMS treatment producing the plants with most mass (Table 3.3). In group 2, the shoot dry weights of *Aloe* 'Gator' and *Aloe* 'Grassy Lassie' were affected by VMS. *Aloe* 'Gator' produced the least dried shoot mass in the medium VMS treatment, while *Aloe* 'Grassy Lassie' produced the most mass with the high VMS treatment (Table 3.4).

In group 1, plant heights of *Aloe* 'Fire Ranch' and *Senecio* Blazin' Glory' were affected by VMS. In both species, the high VMS treatment produced the tallest plants (Table 3.5). In group 2, the height of *Agave* 'Rasta Man' and *Aloe* 'Gator' was affected by VMS. *Aloe* 'Gator' grew the tallest under the low VMS treatment as did *Agave* 'Rasta Man (Table 3.5).

In group 1, average widths of *Aeonium* 'Zwartkop,' *Agave* 'Blue Glow,' and *Senecio* 'Blazin Glory' were affected by VMS. In all three species, the high VMS treatment produced the widest plants, though in *Aeonium* 'Zwartkop' and *Agave* 'Blue Glow' the medium treatment was statistically similar. In group 2, the average widths of *Aeonium* 'Kiwi,' *Agave* 'Rasta Man,' *Aloe* 'Gator,' and *Crassula* 'Campfire' were affected by VMS. In this group however, the low VMS treatment tended to produce the widest plants, except for *Aeonium* 'Kiwi'.

Discussion

There were no apparent trends in any measured growth parameters. All results seemed to be species-specific. This is consistent with the findings of Bousselot et al. (2011). They found that there was no clear division between succulent and herbaceous species in dry down curves because the differences in plant type and water use during dry down was inconsistent within plant type. The general trend in their study however indicated that succulent species retained moisture in the substrate longer than herbaceous species (Bousselot et al., 2011). Bousselot et al. (2011) also noted that after dieback from moisture stress, succulent plants were almost twice as likely to revive as herbaceous plants after rewatering.

While it has been shown that there are optimal soil moisture levels for the growth of ornamental crops, imposition of specific levels has proved difficult (Kiehl et al., 1992). Optimal levels vary based on the crop being grown, the media used and other factors. Plant growth is generally inhibited at moisture levels below 15%, but can vary widely by species. Petunias (*Petunia spp.* Juss.), for example exhibit drought stress at moisture levels below 25% (Van Iersel et al., 2010) but moisture contents between 24% and 34% are ideal for optimal growth in other herbaceous crops such as snapdragon (*Antirrhinum spp.* L.) (Kiehl et al., 1992). In our studies, we noted no drought related damage in any species, even when dried to less than 10% VMC, further establishing the fact that succulents can survive much lower soil moisture levels than most herbaceous crops. Conversely, the only damage seen at the higher VMC treatments was in *Aloe* 'Gator,' where two individuals in the high VMC treatment died. The Plant Disease Clinic (Department of Plant Pathlogy, Physiology, and Weed Science Virginia Tech, specimen #708) identified the bacterium *Psuedomona aeruginosa* as the only pathogen present and advised that while this pathogen is normally opportunistic on stressed or dying tissue, high moisture may exacerbate the problem. This indicates that while most succulents seem to be tolerant of a wide range of VMC's, the response is species-specific.

Our studies failed to isolate an ideal VMC for the optimal growth of potted succulents. Most species studied fared well across the range of treatments administered. Further work needs to be conducted to determine the upper and lower limits for their survival, though it is suspected that those results would be species-specific as well.

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Table 3.1. Weeks to harvest. Crops were harvested when they were deemed 'market ready,' meaning that shoot growth had reached or was actively approaching the edges of the pot.

Species	Weeks To Harvest
Group1	
Aeonium 'Zwartkop'	17
Agave 'Blue Glow'	17
Aloe 'Fire Ranch'	17
Echeveria 'Afterglow'	7
Senecio 'Blazin' Glory'	7
Kalanchoe 'Flapjacks'	9
Group 2	
Aeonium 'Kiwi'	10
Agave 'Rasta Man'	17
Aloe 'Gator'	22
Aloe 'Grassy Lassie'	13
Crassula 'Campfire'	6
Dyckia 'Burgundy Ice'	13
Echeveria 'Violet Queen'	12

Table 3.2. pH and EC values. pH and EC data was collected at potting and harvest using the pour-thru extraction procedure(Wright, 1986). Three individuals per species per volumetric soil moisture treatment were sampled and the results averaged.

Volumetric Soil Moisture

	Low				Med				High			
	pH		EC($ds \cdot m^{-1}$)		pH		EC($ds \cdot m^{-1}$)		pH		EC($ds \cdot m^{-1}$)	
	Begin	End	Begin	End	Begin	End	Begin	End	Begin	End	Begin	End
Group 1												
Aeonium. 'Zwartkop'	6.3	5.6	1.76	2.34	6.1	6.1	1.76	1.73	6.4	6.0	1.77	1.90
Agave 'Blue Glow'	6.0	5.5	1.74	2.46	6.1	5.4	1.62	2.23	5.9	5.3	2.02	2.60
Aloe 'Fire Ranch'	6.2	5.5	1.58	2.07	6.1	5.5	1.64	2.03	6.2	5.6	1.49	2.16
Echeveria 'Afterglow'	6.3	5.5	2.23	1.75	6.2	5.7	1.89	1.17	6.1	5.8	2.35	1.12
Senecio 'Blazin' Glory'	6.1	6.0	1.54	1.32	6.1	6.0	1.56	0.96	6.0	6.2	1.83	0.96
Kalanchoe 'Flapjacks'	5.9	5.7	2.32	2.16	5.7	5.6	1.77	1.83	5.9	5.7	1.93	2.02
Group 2												
Aeonium 'Kiwi'	5.8	5.5	1.83	1.43	5.9	5.5	1.78	1.39	5.7	5.5	1.88	1.33
Agave 'Rasta Man'	6.1	5.6	1.73	2.35	6.1	5.6	1.82	1.89	6.1	5.2	1.78	2.45
Aloe 'Gator'	6.2	6.2	1.80	1.38	6.1	5.8	1.84	1.13	6.1	5.5	1.65	1.09
Aloe 'Grassy Lassie'	6.1	5.5	1.97	2.20	6.2	5.7	1.76	1.88	6.2	5.7	1.74	1.56
Crassula 'Campfire'	6.0	5.9	1.58	1.07	6.0	5.8	1.44	1.05	6.1	5.8	1.62	1.08
Dyckia 'Burgundy Ice'	6.1	5.6	1.66	1.99	6.1	5.7	1.54	1.78	6.1	5.6	1.72	1.50
Echeveria. 'Violet Queen'	6.1	5.7	1.74	0.76	6.0	5.5	1.68	1.17	6.1	5.1	1.82	1.34

Table 3.3. Means of shoot dry weight (g) for plants in group 1, grown using three different soil moisture levels. Data analyzed using Tukey's honest significant difference, P ≤ 0.05, n = 6. . Means followed by the same letter are not significantly different at P ≤ 0.05.

	Shoot dry weights (g)					
Vol. Moisture (%)	*Aeonium* 'Zwartkop'	*Agave* 'Blue Glow'	*Aloe* 'Fire Ranch'	*Echeveria* 'Afterglow'	*Senecio* 'Blazin' Glory'	*Kalanchoe* 'Flapjacks'
10	7.19	2.18	3.21	10.5	2.09c	--
20	8.36	2.60	4.14	10.8	3.27b	--
30	9.51	2.65	3.62	9.2	4.07a	--
P-Value	0.4903	0.1147	0.1334	0.7301	<0.0001	--
HSD	1.89	0.24	0.46	2.1	2.1	--

***Kalanchoe** not dried due to drier malfunction.

Table 3.4. Means of shoot dry weights (g) for plants in group 2, grown using three soil moisture treatments. Data analyzed using Tukey's honest significant difference, $P \leq 0.05$, $n = 6$. Means followed by the same letter are not significantly different at $P \leq 0.05$.

	Shoot dry weight (g)						
Vol. Moisture (%)	*Aeonium* 'Kiwi'	*Agave* 'Rasta Man'	*Aloe* 'Gator'	*Aloe* 'Grassy Lassie'	*Crassula* 'Campfire'	*Dyckia* 'Burgundy Ice'	*Echeveria* 'Violet Queen'
15	5.37	4.71	1.39a	2.45b	6.95	2.46	3.9
25	5.85	4.32	0.68b	3.56ab	7.40	2.64	4.3
35	6.38	4.01	0.88ab	4.31a	8.34	2.67	4.8
P-Value	0.1470	0.3757	0.0308	0.0246	0.1075	0.7245	0.1104
HSD	0.48	0.48	0.24	0.61	0.58	0.30	0.20

Table 3.5. Means of shoot height (cm) at potting and at harvest. Data analyzed using Tukey's honest significant difference, P≤0.05, n=6. Means of end point heights followed by the same letter are not significantly different at P≤0.05.

	Low		Med		High		P-Value (End)	HSD
	Height (cm)							
	Start	End	Start	End	Start	End		
A. 'Zwartkop'	18.5	18.0	17.0	17.2	17.0	19.1	0.7105	2.28
A.'Blue Glow'	1.6	3.9	1.8	4.1	1.5	4.2	0.7310	0.48
A. 'Fire Ranch'	1.8	5.0c	2.0	7.00	1.5	5.8a	0.0005	0.39
E. 'Afterglow'	9.3	11.2	9.7	10.2	9.6	9.3	0.6032	1.80
S. 'Blazin Glory'	4.9	6.4b	5.0	8.1a	5.3	8.6a	0.0001	0.84
0Group 2								
A. 'Kiwi'	5.0	9.5	5.3	10.5	4.6	10.0	0.1639	0.46
A. 'Rasta Man'	7.3	10.5a	6.0	9.3ab	5.8	8.3b	0.0187	0.47
A. 'Gator'	1.2	4.0a	1.0	2.3b	1.0	2.5ab	0.0351	1.67
A. 'Grassy Lassie'	5.5	23.0	7.2	26.5	7.0	23.8	0.1048	4.42
C. 'Campfire	15.7	12.5	15.3	10.2	15.8	13.0	0.4940	2.28
D. 'Burgundy Ice'	2.2	7.6	2.3	7.6	2.5	8.3	0.4538	1.61
E. 'Violet Queen'	1.2	4.0	1.2	4.0	1.0	4.3	0.5486	0.56

Table 3.6. Means of average shoot width (cm) at potting and at harvest. Data analyzed using Tukey's honest significant difference, P≤0.05, n=6. Means of end point widths followed by the same letter are not significantly different at P≤0.05.

	Low		Medium		High		P-Value (End)	HSD
	Average Width (cm)							
	Start	End	Start	End	Start	End		
A. 'Zwartkop'	16.0	14.8b	16.9	19.0a	16.0	19.6ab	0.0355	1.59
A.'Blue Glow'	6.6	9.2b	7.06	10.8a	7.3	10.3a	0.0344	0.47
A. 'Fire Ranch'	8.0	14.4	8.9	16.9	8.6	16.7	0.1914	1.43
E. 'Afterglow'	18.9	24.8	20.8	27.8	20.8	28.3	0.1026	1.67
S. 'Blazin Glory'	8.5	14.3c	11.1	17.6b	11.4	19.7a	<0.0001	2.12
Group 2								
A. 'Kiwi'	8.5	11.8b	8.6	13.1ab	9.1	14.1a	0.0357	1.23
A. 'Rasta Man'	20.8	22.0a	20.5	20.8ab	18.1	18.2b	0.0338	0.77
A. 'Gator'	2.4	5.5a	2.5	3.9b	2.4	4.2ab	0.0182	0.53
A. 'Grassy Lassie'	11.8	27.9	12.1	30.8	11.4	35.0	0.4307	1.86
C. 'Campfire	14.1	21.8ab	13.3	24.2a	13.7	20.5b	0.0246	2.26
D. 'Burgundy Ice'	8.3	14.1	7.9	13.7	7.4	13.7	0.8029	0.84
E. 'Violet Queen'	5.2	8.8	5.2	8.4	5.5	8.9	0.4310	2.15

Figure 3.1. *Senecio* 'Blazin'Glory' volumetric soil moisture (VMS) content (%) vs. time. VMS readings were taken from three plants per rate per day and averaged.

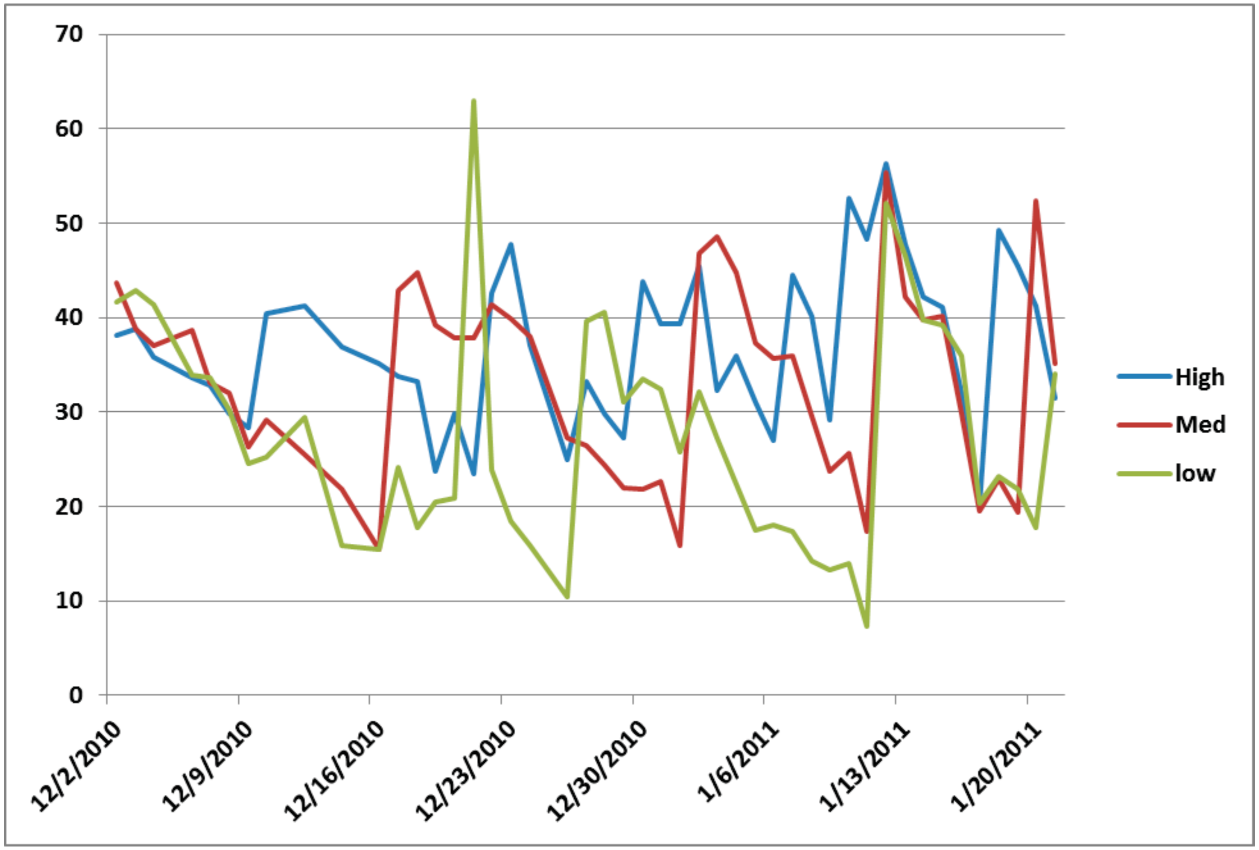
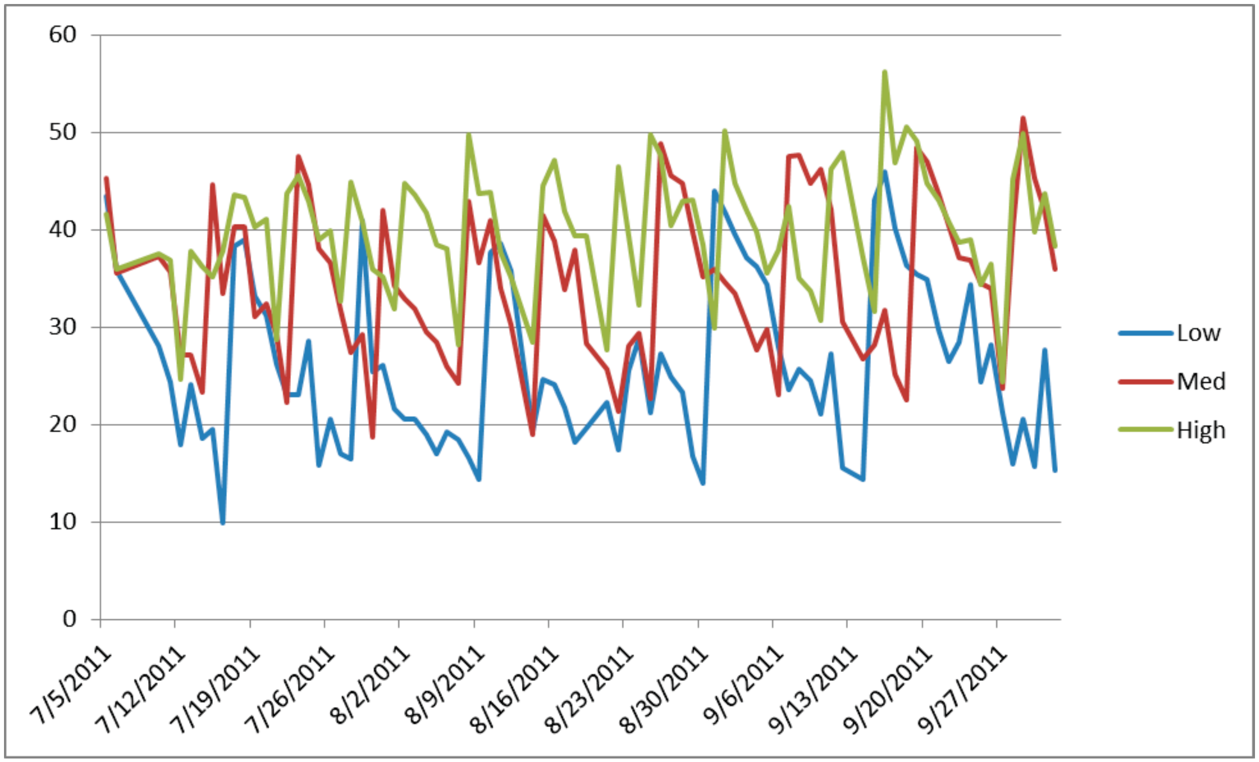


Figure 3.3. Aloe. 'Grassy Lassie' volumetric soil moisture (VMS) content (%) vs. time. VMS readings were taken from three plants per rate per day and averaged.



Chapter 4 - The Effect of Fertilization Rate on the Growth of Potted Succulents

Introduction

Container grown succulent plants have increased in popularity and market share over the past several years. Succulents are becoming popular at retail stores in dish gardens (multiple individuals/species in a shallow container), as specimen (high value, individual) plants, as well being made into many specialty items such as living wreaths or walls (Onofrey, 2011). The green roof industry is also growing in the United States, expanding demand for wholesale succulents, such as sedums (*Sedum spp.* L.) at affordable prices (Rowe et al., 2006). Tissue culture has made more varieties more available to growers as liners, but the problem remains that many of these plants are slow growers, leading to long crop production cycles (turn times). It may be possible to reduce these production times and increase growers' profits by manipulating certain cultural practices such the media in which the plants are grown, irrigation rates, or fertilizer types and/or rates.

Little species-specific information is available on the nutritional needs of containerized herbaceous perennials (Scoggins, 2005). Even less is available on the needs of containerized succulents. That being said, the goal of any fertilization program is to provide the plant with sufficient, but not excessive levels of nutrition (Scoggins, 2005).

Plants require 17 essential elements, three of which are obtained naturally from water and air while all others must come from the soil, growing media or fertilizer regime (Nelson, 1996). Three of these nutrients, known as primary macro nutrients are nitrogen, phosphorus, and potassium, and the ratio of these is what is noted on fertilizer labels (Nelson, 1996).

Soluble salts come from fertilizer, organic matter in the substrate, and dissolved minerals in the irrigation water (Mathers et al., 2007). Soluble salt concentration within the media is most commonly tested by determining the electrical conductivity (EC) of the media in decisiemens per meter ($dS \cdot m^{-1}$). The relationship between the EC of the water (EC_w) and total dissolved salts is the EC_w x 640 = total dissolved salts in $mg \cdot L^{-1}$.

Optimal nitrogen (N) rates vary widely by plant species, the media used, and the form of nitrogen applied. Initial nutrient content for young plants and seedlings should be low so that the plants are not damaged by excess salts (Fonteno, 1996). Full strength fertilization should not commence until the young plants are established and actively growing. Once established, Nelson (1996) recommends nitrogen rates of 100 to 260 $mg \cdot L^{-1}$ N for a variety of herbaceous crops on a constant liquid feed program or 240 to 720 $mg \cdot L^{-1}$ N weekly. Other studies also show that for constant liquid feed, nitrogen rates between 100 and 300 $mg \cdot L^{-1}$ N are ideal for a variety of greenhouse crops (Gamrod and Scoggins, 2006; White and Scoggins, 2005). The purpose of this experiment is to determine the effects, if any of fertilization rates on the growth of potted ornamental succulents.

Materials and Methods

Plant material. Thirteen taxa of ornamental succulents were studied over the course of two experiments. *Agave* L. 'Blue Glow' is a Proven Selections® hybrid. Proven Winners (2012) calls it a 'magnificent hybrid with red-tinged leaves'. The rosettes of foliage have a distinctly blue cast (Proven Winners, 2012). *Agave geminiflora* (Tagliabue) 'Rasta Man' is a selection of *A. geminiflora* marketed by Proven Winners, a 'pincushion' type *Agave* from the subgenus Littaea, group Filiferae. *Senecio cephalophorus* (Compton) 'Blazin' Glory' is a Proven Winners selection of *S. cephalophorus* which is native to the Northern Cape Province of the Republic of South Africa. It displays soft, bluish green foliage and large, numerous orange flowers. *Dyckia* (Dyck) 'Burgundy Ice' is a hybrid by Kelly Griffin. *Dyckia* is one of the most primitive Bromeliad genera, as well as one of the most cold tolerant. *D.* 'Burgundy Ice' is named for its deep purple foliage. Flowers are borne in spikes and have colored bracts (Sajeva and Costanzo, 2000). *Aeonium* (L.) 'Kiwi' displays rosettes of spoon–shaped leaves on short stems that are primarily green with yellow and pink edges. Light yellow flowers appear in late summer (Proven Winners, 2012). *Echeveria* (De Candolle) 'Afterglow' grows in a large rosette of fleshy leaves covered with a lavender colored powder, especially in ideal sun (Proven Winners, 2012). Large spikes of orange flowers emerge from below leaves or sometimes as terminal florescence. *Echeveria* 'Violet Queen' forms rosettes of gray foliage that curls up at the tips, 100 to 125 cm high, with each rosette 150 to 200 cm across (San Marcos Growers, 2011). *Aloe* (L.) 'Fire Ranch' produces fleshy, strap-like green leaves borne in rosettes, and bears numerous red-orange flowers on multiple spikes. *Aloe* 'Grassy Lassie' displays deep green, narrow, grass-like leaves with bright orange flowers. In full sun, the foliage becomes a deep bronze (Proven Winners, 2012). *Aloe variegata* (L.) 'Gator' forms stem less rosettes up to 25 cm tall. Leaves are green to brownish green with white spots arranged in bands. *A.* 'Gator' bears pink flowers on a spike up to 30 cm tall. *Aeonium arboretum* (L.) 'Zwartkop' is an upright growing plant with a fleshy, almost woody stem and rosettes of dark burgundy or purple foliage. Yellow, star shaped flowers form in long clusters from the center of rosettes on mature plants (San Marcos growers, 2011).

Cultural practices and data collection. Studies were conducted on benches in a double-polyethylene covered greenhouse on the Virginia Tech campus in Blacksburg, VA (lat. 37°13' N, long. 80°25' W). Daytime maximum temperature was set at 27°C and nighttime minimum temperature was set at 18°C. The species studied were divided into two groups, grown consecutively due to space constraints. Both groups were grown in Fafard 52 Mix (Conrad Fafard, Inc., Agawam, MA). All plants received a preventative fungicide drench consisting of a tank mix of 0.57 $g \cdot L^{-1}$ Banrot (Etridiazole 15%, Thiophanate 25%) - (Scotts, Marysville, OH) and 0.1 $mL \cdot L^{-1}$ Subdue Maxx® (Mefenoxam 22%) - (Syngenta Crop Protection LLC., Greensboro, NC) the day after they were potted. Plant height, width, and numbers of offsets (new rosettes that can be used for propagation) or leaders (primary branches with secondary lateral branches) and branches (no secondary branching) were measured and recorded at the time of potting and approximately every 2 weeks thereafter. Plants were harvested when deemed market ready (Table 4.1). Market ready was defined as when shoot growth reached or was approaching the edges of the pots. At harvest, shoots were separated from the roots at the soil line, placed in paper bags, and oven dried for one week at 65°C. The dried shoots' weights were then recorded.

Group one. On November 17, 2010 five species of succulents were received from Euro American Propagators (Bonsall, CA). *Aeonium* 'Zwartkop,' *Aloe* 'Fire Ranch,' and *Echeveria* 'Afterglow' were received in 32 cell (199 ml/cell) trays and *Agave* 'Blue Glow' and *Senecio* 'Blazin' Glory' were received in 84 (37 ml/cell) cell trays. *A.* 'Zwartkop' and *E.* 'Afterglow' were potted into 2.77-L round pots, all other species were potted into square 946-ml pots.

Each species was placed into a completely randomized design consisting of four treatments, each with six reps. The treatments were: 0 mg/L^{-1} N (plain water), 50 $mg \cdot L^{-1}$N, 100 $mg \cdot L^{-1}$ N, and 200 $mg \cdot L^{-1}$ N. All plants were irrigated to container capacity with a constant liquid feed of Jack's Cal-Mag 15-5-15 (15N -2.2P-12.5K) (J.R. Peter's, Allentown, PA) at the designated rates when the volumetric moisture content fell below 20%. Average daily light integral (DLI) for group 1 was 19.5 $mol \cdot m^{-2} \cdot d^{-1}$

Group two: On June 29, 2011 five species of succulents were received from Euro American Propagators (Bonsall, CA). *Aloe* 'Gator' was received in a 96 cell (37 ml/cell) tray and potted into 766-ml round azalea pots. *Dyckia* 'Burgundy Ice' was received in an 84 cell tray and potted into the same 766-ml pots. *Agave* 'Rasta Man' and *Aloe* 'Grassy Lassie' were received in 96 cell trays and potted into 1.9-L round Teku (Poppelmann Plastics USA LLC, Claremont, NC) pots . *Aeonium* 'Kiwi' was received in 50 cell trays and potted into the same. *Echeveria* 'Violet Queen' was received on August 10, 2011 and potted into the 766 ml azalea pots.

Each species was placed into a completely randomized design consisting of three treatments, each with six reps. The treatments were: : 50 $mg \cdot L^{-1}$N, 150 $mg \cdot L^{-1}$ N, 250 $mg \cdot L^{-1}$N, and 350 $mg \cdot L^{-1}$N. These rates were adjusted upwards from the group one rates due to poor growth at the 0 $mg \cdot L^{-1}$ N treatment. All plants were irrigated to container capacity with a constant liquid feed of Jack's All Purpose 20-10-20 (20N-4.4P-16.6K) at 150 mg/L^{-1} N when the volumetric moisture content fell below 25%. The irrigation threshold and fertilizer type were adjusted due to experiences with group 1. The average DLI for group two was 23.5 $mol \cdot m^{-2} \cdot d^{-1}$. In addition to the parameters measured in group one, shoot fresh weights were also recorded at the time of harvest for all group 2 plants as a precaution against drier malfunction.

Substrate pH and electrical conductivity measurements. Substrate pH and EC were tested on all crops at the time of potting, and approximately every 2 weeks thereafter until harvest using the pour thru extraction procedure (Wright, 1986). Measurements were taken with an HI 9811 portable pH – EC – TDS meter (Hanna Instruments, Smithfield, RI).

Tissue analysis. Three samples of dried, ground shoot tissue from each treatment of *A.* 'Fire Ranch and *S.* 'Blazin' Glory' were sent to Quality Analytic Laboratories (Panama City, FL) for complete tissue analysis. These taxa were selected because they were the only ones that showed differences in growth versus fertility.

Statistical analyses. Data were analyzed by analysis of variance using JMP9 (SAS Institute, Inc., Cary, NC). Comparison of means among treatments were conducted using Tukey's honest significant difference (HSD) test at $P < 0.05$.

Results

Of the 11 succulent species evaluated, four showed no response to fertility rates. The unresponsive taxa were *Aeonium* 'Zwartkop' and *Echeveria* 'Afterglow' from group 1 and *Aeonium* 'Kiwi' and *Agave* 'Rasta Man' from group 2. Nitrogen rates did not affect offset production or branches or leaders in any of the species studied. In group one, *Echeveria* 'Afterglow' and *Senecio* 'Blazin' Glory' were the fastest to finish, reaching market readiness in 7 weeks from potting (Table 4.1). All other species took 17 weeks . In group 2, *Aeonium* 'Kiwi' was the fastest, at 10 weeks, and *Aloe* 'Gator' was the slowest at 22 weeks (Table 4.1). Across all species, final EC measurements increased and final pH decreased with increasing fertility rates (Table 4.2).

In group one, the dry shoot weights of *Aloe* 'Fire Ranch' and *Senecio* 'Blazin' Glory' were increased by higher fertility rate (Table 4.3). *Dyckia* 'Burgundy Ice' and *Echeveria* 'Violet Queen' were the only species in group 2 whose dry weights were affected by fertility rate. *Echeveria* 'Violet Queen' exhibited the plants with most mass at the 50 mg/L^{-1} N treatment while *Dyckia* 'Burgundy Ice' grew the heaviest plants at the 250 $mg\cdot L^{-1}$ N (Table 4.4). Height was affected by fertility rate only in *Aloe* 'Fire Ranch' and *Senecio* 'Blazin' Glory,' with the higher rates tending to grow taller plants in both species (Table 4.5). The height of none of the plants in group 2 was affected by fertility rates.

Group 1 plants whose width was affected by fertility rates were *Agave* 'Blue Glow,' *Aloe* 'Fire Ranch,' and *Senecio* 'Blazin' Glory.' All taxa that were affected showed increasing width as the fertility rate increased (Table 4.6). In group 2, *Aloe* 'Gator' displayed the same trend while *Dyckia.* 'Burgundy Ice' exhibited the widest plants at the two middle rates (Table 4.6). The tissue analysis of the selected crops revealed increasing concentrations of all macro nutrients with increasing fertility rate (Table 4.7)

Discussion

Although general recommendations are easier for growers to follow, perennials seem to vary widely in response to varying fertilizer rates (Scoggins, 2005). The same seems to be true for succulents. While the measured growth parameters tended to trend upwards with increasing fertility rates in most crops evaluated, the response seems to be species specific. In group 1, all plants that were responsive grew faster with increasing fertility rates, with N rates up to 200 $mg\cdot L^{-1}$. In group 2 however, there was a trend of decreased growth in most species at the highest rate (350 $mg\cdot L^{-1}$), with the middle rates generally performing the best. This is similar to what Twardowski et al. (2012) found with crop/rate results. The exception to this was *Echeveria* 'Violet Queen' which produced the tallest plants and those with the highest shoot dry weights at the lowest fertility rate (50 $mg\cdot L^{-1}$). These results are also consistent with Gamrod and Scoggins (2006) findings that fertilizer rates between 200 and 400 $mg\cdot L^{-1}$ N produced plants of excellent quality.

Scoggins (2005) stated that as fertilizer formulations and ratios vary, most guidelines for growers as given as a range of substrate solution ECs rather than specific nitrogen rates. van Iersel (1999) documented that levels of salts increase when nutrients are applied faster than the plants can absorb them. In both groups, final substrate solutions ECs were very close to the ECs of the fertilizer mixtures. This indicates that the plants were absorbing all the nutrients that were being applied. This is reinforced by the increasing percentage of nitrogen in the plant shoot tissues at increasing rates (Table 4.7). None of the plants displayed any toxicities from excessive fertilizer.

Graham (1987) states that the number and quantity of trace elements is much more important than the amount of nitrogen present in a fertilizer. He further notes that the lack of magnesium, copper, and especially boron is a serious problem. This information could prove invaluable for growers, and while the effect of micronutrients was not studied in this case, further investigation is warranted due to some evidence of nutrient deficiencies across all fertility rates.

The anecdotal information regarding succulents has traditionally held that little or no feeding was required (Graham, 1987). This study has indicated that succulent plants can tolerate medium to high rates of nitrogen fertility. Graham (1987) further states that this idea may be false by noting that all succulents will benefit from a nitrogen fertilizer at the beginning of their active growing period. Timing of fertilizer application should also warrant further study, as what Graham (1987) alludes to, in that succulents need very little fertilizer during less active growth periods (short days), may be true. The observations in these studies are that low to moderate rates of N fertility are required for optimal succulent growth.

Conclusions. The succulent species studied seemed to be very tolerant of a wide range of fertility rates. This information is potentially useful for growers for several reasons. Most importantly among these is that it should demonstrate to growers that they can fertilize their succulent crops using the same regimen that they use on their other herbaceous crops with little fear of doing any damage. Furthermore, a low to moderate amount of fertility may accelerate growth.

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Table 4.1. Weeks to harvest. Crops harvested when they were deemed 'market ready,' meaning that shoot growth had reached or was actively approaching the edges of the pot.

Species	Weeks To Harvest
Group1	
Aeonium 'Zwartkop'	17
Agave 'Blue Glow'	17
Aloe 'Fire Ranch'	17
Echeveria 'Afterglow'	7
Senecio 'Blazin' Glory'	7
Group 2	
Aeonium 'Kiwi'	10
Agave 'Rasta Man'	17
Aloe 'Gator'	22
Aloe 'Grassy Lassie'	13
Dyckia 'Burgundy Ice'	13
Echeveria 'Violet Queen'	12

Table 4.2. pH and EC values. pH and EC data was collected at potting and harvest using the pour-thru extraction procedure (Wright, 1986). Three individuals per species per nitrogen rate were sampled and the results averaged.

Group 1																
N Rate (mg/L)	0				50				100				200			
	pH		EC($ds^{.}m^{-1}$)		pH		EC($ds^{.}m^{-1}$)		pH		EC($ds^{.}m^{-1}$)		pH		EC($ds^{.}m^{-1}$)	
	Begin	End	Begin	End	Begin	End	Begin	End	Begin	End	Begin	End	Begin	End	Begin	End
Aeonium 'Zwartkop'	6.3	6.8	1.08	0.26	6.3	6.4	1.22	0.68	6.6	6.2	1.41	1.4	6.1	5.5	1.96	2.54
Agave 'Blue Glow'	6.2	6.5	0.88	0.28	6.2	5.8	1.01	0.98	6.3	5.4	1.11	1.4	6	5.1	2.02	2.5
Aloe'Fire Ranch'	6.1	6	1.89	0.21	6.3	5.8	0.91	0.71	6.2	5.6	1.22	1.52	6.2	5.2	1.17	2.62
Echeveria 'Afterglow	6.3	6.6	1.61	0.28	6.4	6.4	0.64	0.64	6.2	6	1.4	1.4	6.2	5.7	2.01	2.65
Senecio 'Blazin' Glory'	6.2	6.1	1.12	0.25	6.3	6.4	0.85	0.41	6.3	6.1	1.17	0.84	6.1	5.8	1.99	1.89
Group 2																
N Rate (mg/L)	50				150				250				350			
	pH		EC($ds^{.}m^{-1}$)		pH		EC($ds^{.}m^{-1}$)		pH		EC($ds^{.}m^{-1}$)		pH		EC($ds^{.}m^{-1}$)	
	Begin	End	Begin	End	Begin	End	Begin	End	Begin	End	Begin	End	Begin	End	Begin	End
Aeonium 'Kiwi'	6.3	6.1	1.06	0.5	6.1	5.7	1.53	0.78	6	5.2	2.18	2	5.8	4.9	2.83	2.94
Agave 'Rasta Man'	6.4	6	0.74	0.83	6.4	5.7	1.41	1.66	6.2	5.1	2.02	3.02	6.1	4.7	2.83	4.14
Aloe 'Gator'	6.6	6.1	0.84	0.88	6.5	5.6	1.19	1.64	6.2	5.3	2.15	3.11	6.1	5.1	2.82	3.34
Aloe 'Grassy Lassie'	6.2	6.1	0.83	0.71	6	5.7	1.44	1.49	5.8	5.2	2.11	2.46	5.8	5.1	3.05	3.39
Dyckia 'Burgundy Ice'	6.3	6	0.81	0.59	6.3	5.8	1.02	1.19	6.1	5.4	2.17	2.25	6	5.6	2.59	3.05
Echeveria 'Violet Queen'	6.2	5.9	0.85	0.63	6.2	5.7	1.28	1.36	6.1	5.5	2.14	2.44	6	5.5	2.74	3.11

Table 4.3. Means of shoot dry weight (g) for plants in group 1, grown using four different nitrogen rates. Data analyzed using Tukey's honest significant difference, P ≤ 0.05, n = 6. Means followed by the same letter are not significantly different at P ≤ 0.05.

	Shoot dry weight (g)				
N Rate (mg/L^{-1})	*Aeonium* 'Zwartkop'	*Agave* 'Blue Glow'	*Aloe* Fire Ranch'	*Echeveria* 'Afterglow'	*Senecio* 'Blazin Glory'
0	8.76	1.82	1.71b	10.4	1.29c
50	8.93	2.39	2.66a	11.6	2.39b
100	6.63	2.27	3.01a	9.7	2.63ab
200	6.69	2.14	2.87a	10.3	2.85a
P-Value	0.1856	0.0648	<0.0001	0.7401	<0.0001
HSD	1.34	1.47	0.88	0.74	0.42

Table 4.4. Means of shoot dry weight (g) for plants in group 2, grown using four different nitrogen rates. Data analyzed using Tukey's honest significant difference, $P \leq 0.05$, n = 6. Means followed by the same letter are not significantly different at $P \leq 0.05$.

Mean Shoot Dry Weight (g)

N Rate (mg/L^{-1})	*Aeonium.* 'Kiwi'	*Agave* 'Rasta Man'	*Aloe* 'Gator'	*Aloe* 'Grassy Lassie'	*Dyckia* 'Burgundy Ice'	*Echeveria* 'Violet Queen'
50	6.25	3.27	0.80	3.17	2.49b	4.07a
150	5.99	4.31	1.12	3.02	2.58ab	3.31b
250	6.25	3.96	0.97	3.22	3.25a	3.73ab
350	5.45	4.00	1.19	3.87	2.62ab	3.92ab
P-Value	0.4011	0.322	0.4123	0.2937	0.0227	0.0458

Table 4.5. Means of shoot height (cm) for plants in group 2, grown using four different nitrogen rates. Data analyzed using Tukey's honest significant difference, P ≤ 0.05, n = 6. Means of end point heights followed by the same letter are not significantly different at P ≤ 0.05.

N Rate (mg/L^{-1})	0		50		100		200		P-Value (End)	HSD
	Height (cm)									
	Start	End	Start	End	Start	End	Start	End		
Aeonium'Zwartkop'	18.7	19.8	17.0	20.8	17.8	17.3	16.3	17.0	0.1337	0.93
Agave 'Blue Glow'	1.9	3.6	1.6	3.8	1.9	3.9	1.8	4.3	0.5576	0.46
Aloe 'Fire Ranch'	2.5	3.7b	2.5	5.0a	2.8	5.8a	3.2	5.3a	0.0014	1.68
Echeveria 'Afterglow'	8.8	12.0	9.6	10.8	10.1	13.3	9.7	12.5	0.5587	1.26
Senecio 'Blazin Glory'	4.1	4.2c	4.6	7.1b	4.9	8.6a	4.8	8.4a	<0.0001	0.65

Table 4.6. Means of shoot width (cm) for plants grown using four different nitrogen rates. Data analyzed using Tukey's honest significant difference, P ≤ 0.05, n = 6. Means of end point widths followed by the same letter are not significantly different at P ≤ 0.05.

	0		50		100		200		P-Value (End)	HSD
	Average Width (cm)									
	Start	End	Start	End	Start	End	Start	End		
Group1										
A.'Zwartkop'	16.9	17	18.3	19	17.3	17.5	17.9	15.9	0.1337	1.43
A.'Blue Glow'	6.44	8.69b	6.63	10.1a	6.63	10.6a	6.81	10.1a	0.0027	0.81
A. 'Fire Ranch'	7.88	9.17b	8.25	13.2a	9.92	14.8a	8.83	13.8a	<0.0001	1.55
E. 'Afterglow'	20.10	23.40	21.90	26.30	22.30	25.70	22.30	25.20	0.182	0.74
S. 'Blazin Glory'	8.75	9.5c	9.13	14.2b	9.94	16.1a	9.88	15.9a	<0.0001	2.44
	50.00		150.00		250.00		350.00			
Group 2										
A. 'Kiwi'	8.75	15.20	8.75	15.10	8.91	15.90	8.75	14.40	0.1247	0.22
A. 'Rasta Man'	14.60	19.80	15.00	21.60	15.10	21.00	15.60	21.80	0.2442	0.63
A. 'Gator'	2.76	3.83b	2.67	4.83ab	2.58	4.91ab	2.50	5.60a	0.0461	1.37
A. 'Grassy Lassie'	9.00	34.10	9.33	34.10	9.67	33.10	10.10	40.50	0.741	4.62
D. 'Burgundy Ice'	7.58	16.2b	7.25	16.9ab	8.17	18.4a	8.08	15.3b	0.0007	0.76
E. 'Violet Queen'	5.25	8.58	5.33	5.58	5.08	8.50	5.58	8.50	0.9694	3.51

Table 4.7. Percent nitrogen in shoot tissue of selected plants. Tissue analysis performed by Quality Analytic Laboratories, Panama City, Fl.

	Tissue % N	
Rate	*Aloe* 'Fire Ranch'	*Senecio* 'Blazin Glory'
0	1.50	1.80
50	2.65	3.21
100	2.70	4.24
200	2.93	4.82

Chapter 5 - The Effect of Plant Growth Regulators on the Growth of Potted Ornamental Succulents

Introduction

Container grown succulent plants have increased in popularity and market share over the past several years. Succulents are becoming popular at retail stores in dish gardens (multiple individuals/species in a shallow container), as specimen (high value, individual) plants, as well being made into many specialty items such as living wreaths or walls (Onofrey, 2011). The green roof industry is also growing in the United States, expanding demand for wholesale succulents, such as sedums (*Sedum spp.* L.) at affordable prices (Rowe et al., 2006). Tissue culture has made more varieties more available to growers as liners, but the problem remains that many of these plants are slow growers, leading to long crop production cycles (turn times). It may be possible to reduce these production times and increase growers' profits by manipulating certain cultural practices such as irrigation and fertilization regimes, or the media in which the plants are grown. Plant growth regulators (PGRs) may also be a useful tool for efficiently producing quality potted succulents.

Plant growth regulators (PGRs) are chemicals intended to manipulate plant characteristics. PGRs can be used during propagation to increase seed germination, improve rooting of cuttings, and to trigger growth in tissue culture (Carey, 2008). In production applications, PGRs may be used to increase or decrease growth rate, chemically pinch plants, induce buds to break dormancy or apical dominance, and to delay flowering (Carey, 2008). Some PGRs are simply synthetic plant hormones and are intended to mimic the action of actual hormones found in plants. Others are designed to inhibit the synthesis, reception, or metabolism of hormones, thus negating their effects (Carey, 2008).

Configure® is a PGR from Fine Americas (Walnut Creek, CA) introduced in 2007. Configure's active ingredient, N-(phenylmethyl)-1H-purine-6-amine, also known as benzyladenine or 6-BA is a synthetic cytokinin. Cytokinins are plant hormones responsible for the release of lateral buds from apical dominance and the promotion of cell division and differentiation (Latimer and Whipker, 2010). Plant responses to Configure vary widely by species, variety, growth stage of plant, water and fertilizer management, light, and other cultural influences (Latimer and Whipker, 2010).

Augeo™ (OHP, Mainland, PA) is a relatively new PGR using 2,3:4,6-di-o-isopropylidene-2-keto-L, gulonate, commonly known as dikegulac-sodium as its active ingredient. The product information bulletin from OHP claims that Augeo™ "enhances overall structure and appearance by reducing apical dominance and promoting lateral branching" (OHP, 2010). This results in a fuller, more compact plant that may be more appealing to consumers. Augeo™ disrupts cell wall activity, causing a pinching effect on the plant (OHP, 2010).

Some specific work has been done on succulent species with Configure. A foliar application of Configure at 400 $mg \cdot L^{-1}$ increased offsetting and flowering in *Echeveria setosa*, increased offsets on *Sempervivum* varieties, and increased the number of flower stalks on *Aloe* 'Grassy Lassie' (Carey, 2008). No documented research was found regarding the use of Augeo on succulents.

Materials and Methods

Plant material. Seven species of ornamental succulents were studied over the course of two groups. *Agave* L. 'Blue Glow' is a Proven Selections® hybrid. Proven Winners (2012) calls it a 'magnificent hybrid with red-tinged leaves'. The rosettes of foliage have a distinctly blue cast (Proven Winners, 2012). *Senecio cephalophorus* (Compton) 'Blazin' Glory' is a Proven Winners selection of *S. cephalophorus* which is native to the Northern Cape Province of the

Republic of South Africa. It displays soft, bluish green foliage and large, numerous orange flowers. *Crassula coccinea* (L.) 'Campfire' is a branching succulent with light green propeller shaped leaves that mature to a bright red color. Small, white flowers are dispersed along the stem (San Marcos Growers, 2011). *Echeveria* (De Candolle) 'Afterglow' grows a large rosette of fleshy leaves covered with a lavender colored powder; especially in ideal sun (Proven Winners, 2012). Large spikes of orange flowers emerge from below leaves or sometimes as terminal florescence (Proven Winners, 2012). *Aloe* 'Fire Ranch' has thick, strap-like, deep-green foliage in rosettes. It bears numerous red-orange flowers on multiple spikes.

Substrate treatments, cultural practices and data collection. Studies were conducted on benches in a double-polyethylene covered greenhouse on the Virginia Tech campus in Blacksburg, VA (lat. 37°13' N, long. 80°25' W). Daytime maximum temperature was set at 27°C and nighttime minimum temperature was set at 18°C. The species studied were divided into two groups, grown consecutively due to space constraints. All plants received a preventative fungicide drench consisting of a tank mix of 0.57 $g \cdot L^{-1}$ Banrot (Etridiazole 15%, Thiophanate-methyll 25%) - (Scotts, Marysville, OH) and 0.1 $mL \cdot L^{-1}$ Subdue Maxx® (Mefenoxam 22%) - (Syngenta Crop Protection LLC., Greensboro, NC) the day after they were potted. Plant height and width, and numbers of offsets (new rosettes that can be used for propagation) or leaders (primary branches with secondary lateral branches) and branches (no secondary branching) was measured and recorded at the time of potting and approximately every two weeks thereafter. Plants were harvested when deemed market ready , defined as when shoot growth of about half of the individuals in the study reached or was approaching the edges of the pots. At harvest, shoots were separated from the roots at the soil line, placed in paper bags, and forced air oven dried for one week at 65°C. The dried shoot weights were then recorded.

Group 1. On November 17, 2010 four species of succulents were received from Euro American Propagators (Bonsall, CA). *Aloe* 'Fire Ranch' and *Echeveria* 'Afterglow' were received in thirty two cell trays and *Agave* 'Blue Glow' and *Senecio* 'Blazin' Glory' were received in 84 cell (45 ml/cell) tray *E.* 'Afterglow' was potted into 2.77-L round pots, all other species were potted into square 946-ml pots.

Each species was placed into a completely randomized design consisting of four treatments, each with six replications. Treatments applied by foliar spray were: 0 $mg \cdot L^{-1}$, 250 $mg \cdot L^{-1}$, 500 $mg \cdot L^{-1}$, and 1000 $mg \cdot L^{-1}$Configure. All plants within the study were irrigated to container capacity with a constant liquid feed of Jack's Cal-Mag 15-5-15 (15N -2.2P-12.5K) (J.R. Peter's, Allentown, PA) at 100 $mg \cdot L^{-1}$ N when the average volumetric moisture content of three plants per treatment fell below 20% as measured by a Waterscout SM 100 soil moisture sensor (Spectrum Technologies, Plainfield, IL). Average daily light integral (DLI) for group 1 was 19.5 $mol \cdot m^{-2} \cdot d^{-1}$.

Group 2: On June 29, 2011 two species of succulents were received from Euro American Propagators (Bonsall, CA). *Crassula coccinea* 'Campfire' was received in 50 cell (111-ml/cell) trays on July 20, 2011 and potted into the 1.9-LTeku pots. *Echeveria* 'Violet Queen' was received on August 10, 2011 and potted into the 766-ml azalea pots.

Each species was placed into a completely randomized design consisting 8 treatments, each with six replications. Treatments were: 0 $mg \cdot L^{-1}$ control, 250 $mg \cdot L^{-1}$ Configure, 500 $mg \cdot L^{-1}$ Configure, 1000 $mg \cdot L^{-1}$, 400 $mg \cdot L^{-1}$ Augeo, 800 $mg \cdot L^{-1}$ Augeo, 1600 $mg \cdot L^{-1}$ Augeo, or a 500 $mg \cdot L^{-1}$ Configure/800 $mg \cdot L^{-1}$ Augeo tank mix. All plants were irrigated to container capacity with a constant liquid feed of Jack's All Purpose 20-10-20 (20N-4.4P-16.6K) at 150 mg/L^{-1} N when the volumetric moisture content fell below 25% as measured by a Waterscout SM 100 soil moisture sensor. The watering threshold was adjusted due to experiences with group 1. A destructive harvest was performed on *Crassula* 'Campfire' in order to count branches and leaders. Shoot fresh weights were taken for group 2 at the time of harvest as a precaution against drier malfunction. Average DLI for group 2 was 23.5 $mol \cdot m^{-2} \cdot d^{-1}$.

Substrate pH and electrical conductivity (EC) measurements. Substrate pH and EC was tested at the time of potting and at harvest using the pour thru extraction procedure (Wright, 1986). Measurements were taken with a Hanna HI 9811 portable pH – EC – TDS meter (Hanna Instruments, Smithfield, RI).

Statistical analyses. Data were analyzed by analysis of variance using JMP9 (SAS Institute, Inc., Cary, NC). Comparisons of means among treatments were conducted using Tukey's honest significant difference (HSD) test at $P < 0.05$.

Results

Configure application had no effect on any group 1 species at any rate, for any of the measured growth parameters (data not shown). In group 2, the PGR application affected width, and numbers of branches and leaders of *Crassula* 'Campfire,' (Table 5.1), and offset production of *Echeveria* 'Violet Queen' (Table 5.2). *Crassula* 'Campfire increased production of branches and leaders as the concentration of Configure increased. The Configure/Augeo tank mix results were similar to the 500 or 1000 $mg \cdot L^{-1}$ Configure treatment (Table 5.1). *Echeveria* 'Violet Queen' increased offset production as Configure rates increased, again with the tank mix rate being similar to the higher rates of Configure (Table 5.2)

Discussion

Carey (2008) studied the effects of Configure on many species of plants, including succulents, with mixed results. His observations on *Aloe* and *Agave* hybrids showed no effects with foliar sprays up to 800 $mg \cdot L^{-1}$. That is consistent with the results of our studies. Carey et al. (2010) found that 400 $mg \cdot L^{-1}$ Configure improved offsetting and accelerated flowering of many species of herbaceous perennials. The results of our study showed some increased offset production in *Echeveria* 'Violet Queen,' but the plants did not flower. Configure also induced lateral and basal branching in *Senecio* at rates from 50 to 400 mg·L^{-1} (Carey, 2008). In our study, *Senecio* 'Blazin' Glory' was unresponsive to Configure application. Studies of BA and dikegulac (the active ingredients in Configure and Augeo, respectively) showed no effects on *Crassula* species at up to 50 mg·L^{-1} BA or 500 mg·L^{-1} dikegulac (Lyons and Hale, 1987). The unresponsiveness to dikegulac or Configure in combination with Augeo was observed in this study as well, though *Crassula* 'Campfire' was affected by Configure at higher rates.

Branching in *Crassula* 'Campfire' increased dramatically with increasing rates of Configure. At rates of 500 mg·L^{-1} and higher however, there was significant callus formation at the nodes, which was unsightly and would be detrimental to the marketability of the plant. Interestingly, *Crassula* 'Campfire' produced the highest number of branches with the combination of Configure and Augeo. This was significantly more than either the 500 mg·L^{-1} Configure or 800 mg·L^{-1} Augeo treatment though it was only slightly greater than the 1000 mg·L^{-1} Configure treatment. This indicates that there may have been some sort of interaction between the chemicals and further study may be warranted.

The question remains why the group 1 plants displayed no effects, regardless of Configure rates. Latimer and Whipker (2010) note that Configure is simply not effective on all plants, though Carey (2008) had some effects on plants within the same genera that we did not. This leads to questions of uptake. Further research is necessary to determine if conditions such as the time of day or time of year may affect on the uptake and effectiveness of PGR applications on succulents. Perhaps applying chemicals to CAM plants in the morning when their stomata are closed inhibits uptake of the application.

Are PGRs a useful tool for the production of ornamental succulents? It seems to be a species, even cultivar specific question. With the exception of *Crassula*, at high rates, there were no phytotoxic or detrimental effects. Due to this, growers may use PGRs on succulents with little fear of damaging a crop, though the anticipated results may or may not occur.

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Table 5.1. Number of leaders, number of branches, height, and width of *Crassula* 'Campfire' at harvest after treatment with Configure or Augeo. Data analyzed using Tukey's honest significant difference, $P \leq 0.05$, $n = 6$. Means followed by the same letter are not significantly different at $P \leq 0.05$.

Treatment ($mg \cdot L^{-1}$)	Number of Leaders	Number of Branches	Height (cm)	Width (cm)
0 Control	2.00b	31.0c	14.0	25.8ab
250 Configure	13.3a	66.3ab	12.5	22.5ab
500 Configure	6.00b	48.3bc	14.2	20.6ab
1000 Configure	16.4a	75.6a	15.0	19.4b
400 Augeo	3.50b	44.7bc	12.3	28.0ab
800 Augeo	2.33b	35.6c	14.5	28.7a
1600 Augeo	2.67b	35.0c	15.7	28.8a
500/800 Configure/Augeo	15.8a	79.0a	14.0	20.4ab
P-Value	<0.0001	<0.0001	0.679	0.0019
HSD	1.64	7.58	3.07	2.74

Table 5.2. Number of offsets, height, width and shoot dry weight of *Echeveria* 'Violet Queen' at harvest after treatment with Configure and Augeo. Data analyzed using Tukey's honest significant difference, $P \leq 0.05$, n = 6. Means followed by the same letter are not significantly different at $P \leq 0.05$.

Treatment ($mg \cdot L^{-1}$)	Number of Offsets	Height (cm)	Width (cm)	Shoot Dry Weight (g)
0 Control	0.17b	4.5	12.0	4.13
250 Configure	1.50ab	4.8	10.5	4.58
500 Configure	2.50ab	4.8	11.3	4.69
1000 Configure	4.17a	4.6	10.3	4.45
400 Augeo	1.17b	4.8	10.8	4.35
800 Augeo	1.33ab	5.3	11.6	4.67
1600 Augeo	0.50b	5.3	11.8	4.82
500/800 Configure/Augeo	1.67ab	5.0	11.3	4.24
P-Value	0.0047	0.1964	0.1185	0.4517
HSD	0.94	0.34	0.70	0.34