VEGETATION IN DRYLAND BIORETENTION SYSTEMS

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1 ABSTRACT

Suburban development in dry-land locations requires stormwater controls that are both functional and visually acceptable thus requiring an understanding of establishment and growth of drought-tolerant vegetation that matches dry soil and climatic conditions. Profiled here is a case study of four projects, constructed from 2007-2014 under drought conditions, deploying native and non-native drought tolerant species planted under different aesthetic themes in four settings: residential green space, residential street ROW, residential lot, and civic gardens. The systems use sand and pervious engineered growing media to allow for stormwater infiltration and underdrains to de-water in non-percolating sub-soils. Described here are the proposed vegetative selections and landscape design intentions. Results of a field inventory showed good survival and health in Ilex vomitoria (Yaupon Holly), Acer ginnala (Amur Maple), Perovskia atriplicifolia (Russian Sage), Hemerocallis spp. (Daylilies), Artemisia 'Powis Castle' (Wormwood), Salvia greggi (Autumn Sage), and Schizachyrium scoparium (Little Bluestem). The mesic-hydric adaptive growers of Itea virginica (Virginia Sweetspire), and Juncus effusus (Rush) had limited survival and poor health. And in a comparative sub-set study using in-field Normalized Differential Vegetation Index (NDVI) recordings, street right of way bioretention systems (0.48) were more productive than traditional tree lawns (0.38). Recommended are two plant palette leads for consideration.

1.1 Keywords

Rain garden, vegetation, dryland, bioretention, green infrastructure, plants

2 INTRODUCTION

We live in an increasingly urbanized world and cities in dryland locations experiencing growth in population require climatically responsive forms of contemporary stormwater infrastructure. Although, arid or semi-arid cities may experience less annual rainfall than more temperate locations, plains locations can experience high intensity storm events coupled with long periods of drought. This pattern of extreme weather requires 'green' infrastructure and its vegetation to be matched to local climate and growing conditions. The aesthetics and management practices of green infrastructure must also be in line with the context of the civic stormwater infrastructure.

The process of urbanization appropriates natural resources for human uses and alters the physical and biogeochemical environment of local, and often distant, natural systems (Rees and Wackernagel 1992). To counteract these impacts, green infrastructure (GI), a network of landscape elements that mimic natural systems with vegetation, soils, and natural processes, is being proposed as a form of quasi-contextual infrastructure to accommodate urbanization (Bolund and Hunhammer 1999; Benedict and McMahon 2006). GI comes in a variety of forms (green space, holding ponds, rain gardens, green roofs, etc.) The main objective of GI design has been to avoid stormwater transport directly to sewer systems and water bodies to prevent flooding and downstream water quality degradation. GI has been popularized through the multidisciplinary approaches of Low Impact Development (LID) (LID 2014), and has found its way into the regulatory sphere of stormwater control measures (USEPA 2014). For this reason it is important to explain and attempt to use cross-disciplinary terminology when discussing a GI approach.

Late twentieth century green space communities and conservation sub-division developments using ecological planning approaches contributed to the success of an alternative way of managing urban water resources through the processes of infiltration and evapotranspiration (McHarg 1971, Girling, C. and Kellet 2002, Yang et al 2010). The term 'green infrastructure' would come later as rebranding of this approach (Benedict and McMahon 2002). More recently, in the effort to optimize these stormwater approaches from an edaphic perspective on smaller scales the study and conceptualization of 'bioretention' was advanced (Hsieh and Davis 2005). *Bioretention systems* are stormwater mitigation measures that use low impact approaches to reduce discharge and improve runoff water quality (Hunt et al 2015). The term bioretention system includes rain gardens, which may have intended aesthetic purposes; or biofiltration systems which are implemented for particular pollutant material removal. The term 'bioretention cell' is used when referring to a single contained part of the system.

In dryland regions stormwater has been managed through bioretention systems to slow and retain runoff, while capturing pollutants and creating specific aesthetics in residential communities (Wenk and Gregg 1998). The aesthetics and functionality are created by unique and particular soil and plant selections that can thrive in inundation and drought. The matching of vegetation type to hydro-periods and individual species to soil moisture conditions is critical to the success of dryland bioretention system (Li, et al. 2011 and Houdeshel et al. 2015). As studies on bioretention systems have focused mainly on understanding and optimizing soils, chemistry and hydrology, while the literature on plants has supported the design profession with publications of plant lists. Previous publications address plant selection by vegetative type; trees, shrubs, etc. (Dunnett and Clay 2007) individual traits (Fairfax county 2007) and aesthetic characteristics of formality (Missouri Botanical Gardens 2015). Common to all publications is the matching of vegetation with the expected soil hydrology and regional climate. This paper aims to present the observations of vegetative survival and health in applied dry land projects and offer recommendations towards lead plant palettes for future bioretention systems.

3 PROJECTS SITES

Four bioretention projects in five locations have commenced in the Oklahoma south central plains since 2007 (Figure 1). The projects occur in residential, civic, institutional and commercial land uses in three Oklahoma watersheds provide examples of a dryland approach to rain garden design. Trailwoods Greenstreet, (Norman, OK), Bioretention Cells (Grove, OK) Carrington Lakes (Norman, OK) and Deerfield Estates (Oklahoma City, OK) utilize highly porous growing media with sub-drains where dry-adapted rain garden vegetation is used to improve stormwater quality while providing a range of garden aesthetics. Across the projects, 43 individual gardens have been planted in bioretention systems.

The South Central plains region experiences extreme weather conditions with long hot and dry periods. Droughts are frequent and coupled with both high and low temperatures. Rainfall has high spatial, volumetric and intensity variation. Convection thunderstorms, common in the region, can drop 100 year rain event in a small basin and no rainfall in the adjacent basin. Thunderstorms are commonly followed by long periods without rainfall. These extreme conditions create difficulties for vegetative establishment and consistent visual appearance making the region acceptable for studying dryland landscape installations.

Figure 1. Map showing project locations in Norman, OK (Carrington Lakes), Oklahoma City (Deerfield Estates), Stillwater, OK and Grove, OK.

3.1 Grove and Stillwater

Ten bioretention cells have been constructed in a variety of land use settings in Grove and Stillwater, Oklahoma (Figure 2). Cells range in size from 19 m3 to 435 m3 (25 to 569 yd3), and embrace residential, commercial, and public sites. The project as part of an ongoing study to demonstrate the pollutant removal effectiveness of bioretention technology of cells amended with fly ash (Chavez et al., 2013). Of the ten cells, two are residential properties, six are public or municipal properties, and two are commercial properties. They were design in 2005-06 and constructed in 2007. All the Grove cells and one of the two Stillwater cells possessed organically amended topsoil at the surface with 30 to36 inches of Dougherty sand mixed with 2.5% fly ash (for phosphorus retention) with subdrains overlaying parent clay soils. The other Stillwater cell is similar but without the fly ash mixed into the media. All the cells in Grove and Stillwater are covered with approximately 1 inch of hardwood mulch.

Figure 2. The Grove project has 8 planted bioretention cells. Aesthetic maintenance ranges a highly maintained civic site (left) a self-organized commercial site (middle) and intensively maintained residential site (right).

3.2 Carrington Lakes

The bioretention project at Carrington Lakes was to integrate into the site development plan to create 11 rain gardens as mid-stream interceptors that are phased in with each residential neighborhood section. Currently the community has installed 8 rain gardens and one biofiltration system. All the rain gardens are located in the publically accessible green space, cleansing 5 acre basins delivering surface flow runoff to constructed lakes and ponds. The bioretention catch first flush events form the development prior to water entering the pond. Aesthetically, the gardens offer flowering perennials and shrubs to a verdant pastoral style landscape and are managed by the community homeowners association. Located in Northwest Norman, Oklahoma in the Little River basin of the Lake Thunderbird watershed, the community is a non-gated single family residential neighborhood covering 173 acres with 27 acres of designated public open space, including 9 acres of lakes and 2 miles of pedestrian trails (Figure 3). The cells in Carrington Lakes contain media of 70% lightweight expanded clay, 20% Dougherty sand, and 10% amended organic existing clay soils with sub-drains overlaying parent clay soils.

Figure 3. Carrington Lakes has 7 rain gardens in the greenspace and public areas. Left to right entry monument, greenspace, pond, rain garden.

3.3 Trailwoods

Trailwoods residential community is located in the northern section of Norman, Oklahoma in the Little River basin of the Lake Thunderbird watershed. The design and monitoring of the project are funded by an EPA Grant provided through the Oklahoma Conservation Commission. The construction was funded through a private sector partner, Ideal Homes. The project goals are to help clean the stormwater runoff within the watershed that supplies the City of Norman's drinking water. The rain garden is designed to clean stormwater through the use of plant material and specialized engineered soils. The project is designed streetscape within the public right-of-way of the neighborhood street (Figure 4). The streetscape is intended to mitigate surface water flows and nutrient loads. Trailwoods Greenstreet was created by offering public- private rain gardens at the street edge to improve water quality and enhance community. The Master Plan was completed in the Winter of 2010, construction of the homes began in March of 2011, and the last home was finished in July of 2013. Monitoring equipment was installed in the Spring of 2013 and was completed and became operational in October of 2013. The cells in Trailwoods contain media of 70% lightweight expanded clay, 20% Dougherty sand, and 10% amended organic existing clay soils with sub-drains overlaying parent clay soils.

Figure 4. Trailwoods has 17 street side rain gardens. Left to right early Summer display of Autumn Sage, dryland plants, and homeowners participating in stewardship.

3.4 Deerfield Estates

Deerfield Estates is located in Oklahoma City, Oklahoma in the Hogg creek basin of the Little River basin and has a collection of five residential bioretention cells designed in different thematic concepts of "Strong Frames", "Forest Brook", and "Green Swing". The gardens are placed within homeowners' property lines that also correct issues within each site (Figure 5). All the gardens educate the homeowners and their neighbors of the use of native plant material for Oklahoma that not only requires little maintenance, but also beautification of their outdoor space. The bioretention cells, also known as rain gardens, have many attributes; such as: a storage location, physical filter, chemical reactor, and a biological degradation system for stormwater and wastewater. This project serves to reduce non-point source pollution urban runoff, phosphorus and sediment applications that may be applied by homeowners. Construction began in the Summer of 2013 and finished in the Spring of 2014. Maintenance and construction corrections were continued throughout the summer; as well as working with homeowners through stewardship maintenance/practices. The cells at Deerfield Estates contain sorted sand media overlaying sandy, well-drained soils. Only one of the cells at Deerfield estates has an underdrain, because of a relatively shallow water table at that site. All the cells at Deerfield Estates are covered with approximately 1 inch of hardwood mulch.

Figure 5. Deerfield Estates three rain gardens and two bioretention systems.

4 VEGETATION

4.1 Conceptualization

The cells were conceptualization by different design teams influencing the selection of vegetation. A common goal was achieving establishment with drought tolerant species in highly porous soils, and stewardship of the vegetation relied on creating gardens that served additional purposes. In Grove and Stillwater imported sand was the primary substrate; in Trailwoods and Carrington Lakes expanded clay was used and in Deerfield Estates sand from the project sites was used.

Within vegetation selection, concepts were developed through visualization studies that addressed each site's context. The stakeholder's input were taken; including property owners and owner's representatives for new construction. Conceptual imagery was combined with a materials palette that included vegetation and substrates to aid in plant survival and meet owners aesthetic and maintenance expectations (Figure 6). Plant typologies were selected based on each site's developing design intent. For example, entry and gateway palettes were developed for residences at Deerfield Estates. The individual species possessed aesthetic traits to contrive the setting, while having high likelihood of establishing and surviving in the edaphic and climatic conditions. These conceptuals were used to gain feedback from stakeholders and the design team. The revised design proposals entered schematics, or in some projects went directly into construction drawings.

Another commonality of the projects was that plant selection targeted nursery available species in the South Central plains. They were a mix of exotic horticultural varieties and natives. A few genera common to all projects were Hemerocallis spp., Ilex spp., Pennisetum spp. and Betula spp. Distinction of vegetation was more common in the projects and individuals cells and gardens.

4.2 Implementation and Establishment

The gardens were installed by various contractors with standard horticulture installation practices. Necessary site work was performed and substrate was prepared or installed. The installation of vegetation occurred primarily through plugs, pots, and container plants. The majority of trees were balled and burlapped. Installation of plants occurred throughout the year with a concentration in the summer months. Sites were established under varying irrigation regimes. Trailwoods and residential gardens in Grove and Deerfield Estate received more irrigation. At Carrington Lakes routine irrigation was used provide to certain gardens, while others received little to no irrigation.

Figure 6. Imagery of the conceptualization process: Bioretention cells and rain gardens were conceptualized with substrates and vegetation in palettes that met various contextual issues to aid establishment and ownership stewardship. These gardens took on landscape themes such as thresholds, gateways, landscape follies, foci, and edges

5 METHODS

The recording of vegetation included site observation, field inventory, photographic recordings, and Normalized Difference Vegetation Index (NDVI). Duration and frequency varied based on time of installation and age of project. Site observation included random field visitation during the growing periods. Young (>2 years), establishing projects received more frequent visitation than older, established projects. In the Grove, Stillwater and Trailwoods sites vegetation community composition was recorded as a percent cover of the cell or garden through census field measurement of each garden. Photographic records of species and gardens were used to assess the health quality. Health was determined by plant form, leaf color, and canopy density in five categories based on the characteristics of a model species: Very good, Good, Present, Struggling, and Not present were used to qualify the level of health. Survival was compared to quantity when installed when quantities were known. When quantities were unknown field inspection recorded individual plants of the species when missing from massing and rows. This was indicated as high (>85%), medium (84-50%), and low (<50%). These were used for all types of vegetation.

To explain vegetative performance Normalized Difference Vegetation Index (NDVI) was recorded in 2014 in Trailwoods bioretention cells. NDVI is calculated from the visible and near-infrared light reflected by vegetation as a measure of Photosynthetically Active Radiation (PAR), biomass and ecosystem productivity. NDVI at the plant level is linked to plant health (Guo et. al 2008) at the landscape and watershed scales have been linked to stream health (Griffith et. al 2002) and in green roofs used for plant establishment in water deficit conditions (Nektarios et. al 2013). NDVI was used to examine the productivity of the vegetation in the bioretention cells as single point- in-time measurement late in the growing season and compare to the ground plain in conventional tree lawns. A handheld NDVI meter (GreenseekerTM) took one recording per 50 m2. The measurements were used for the comparison of cell to one another and non-garden sites in the control basin. The comparative analysis used a matched pair T-test on 56 pairs to determine significant difference in mean values at the 0.05 level.

Climate was warmer with less than normal precipitation throughout the period of bioretention cell establishment. Climate data was taken from Will Rodger's Airport for all sites, Oklahoma City, Oklahoma (NOAA). Between 2007-2014 Central and Eastern Oklahoma experienced three years of normal temperature and precipitation and four years of drought and extreme high and low temperature. In 2010-2011 the sites experienced extremely dry conditions including record potential evapotranspiration during the growing seasons and record high air temperatures (NOAA 2015). In 2011, Oklahoma City recorded the hottest days on record (113o F) and most consecutive days over 110o and 105o F (NOAA 2012).

6 PERFORMANCE

In the Grove, Stillwater and Trailwoods sites vegetation community composition was recorded as a percent cover of the cell or garden. Presented in Figure 7 are some observed trends. In highly maintained sites employing weed control the plant community remained similar to the original plant palette and species failing to establish could be identified. These cells were dominated by trees or shrub masses that expressed the aesthetic design intent of the setting. For example the Grand Lake Association bioretention cell was maintained with weed control to facilitate a "clean" ground plane. Deceased plants were not replaced leaving a larger percentage of bare soil or mulch. These changes also allowed for an aesthetic dominance of Pine and Birch in the view. On the other hand when maintenance was removed the plant community shifted towards greater coverages of volunteer species. These species were native and exotic volunteers. At Elm Creek Plaza site Johnson Grass increased to cover the ground plane while Ambrosia spp. (Ragweed) emerged as a native weed. The site contained Amur maple, Loblolly Pine and Shrubby Cinquefoil from the original palette.

The rain gardens possessed a higher mean NDVI (0.48) when compared to the lawn (0.38), $t(55) = 3.38$, $p < .001$) using JMP software (Figure 8).The higher values signify greater quantities of plant biomass in the gardens and correlate to nutrient and water capture in plants. Deerfield Estates was assessed upon installation and future recordings are planned. A comparative analysis across projects may be possible.

Plants that were observed across the majority of projects included Ilex vomitoria (Yaupon Holly), Acer ginnala (Amur Maple), Perovskia atriplicifolia (Russian Sage), Hemerocallis spp. (Daylilies), and Artemisia 'Powis Castle' (Wormwood). Natives that show presence and good health in several locations include Salvia greggi (Autumn Sage), and Schizachyrium scoparium (Little Bluestem). Species of native primrose Calyophus drummundianus var. berlandieri (Texas Primrose) and native cultivars Echinacea ButterflyTM Julia (Coneflower) were used rarely but have shown isolated success.

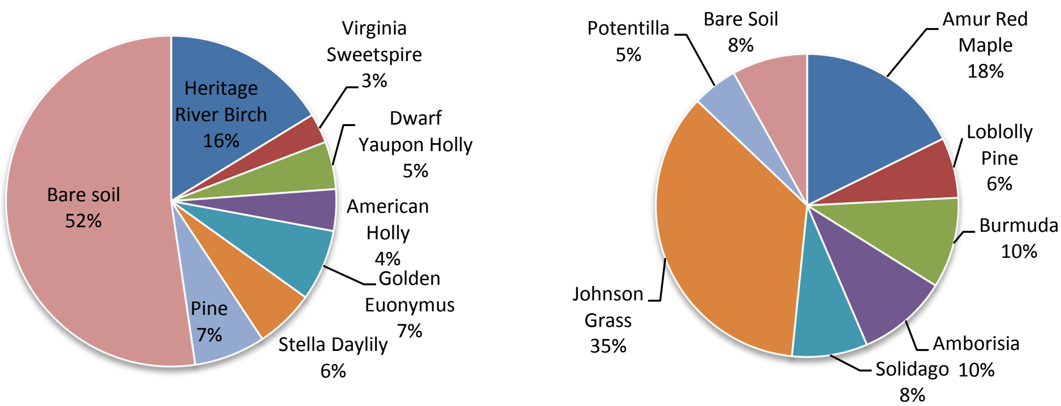

Figure 7. Grove Ok: Two bioretention cells experience different plant community composition over 5 year period. Grand Lake Association (left) was intensively maintained with weekly weeding program while Elm Creek Plaza (right) was allowed to self-organize.

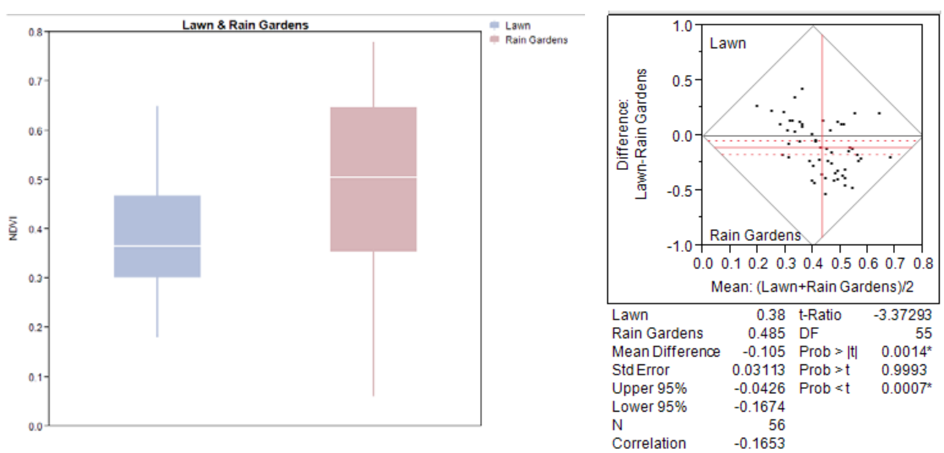

Figure 8. Trailwoods NDVI: The paired basin analysis project at Trailwoods shows the rain gardens possess plant productivity (NDVI) than conventional tree lawns. NDVI value differences with means outside the 95% confidence interval (left) and statistical *t*-value difference.

Species that failed to establish were more mesic-hydric growers including *Itea virginica* (Virginia Sweetspire), and *Juncus effusus* (Rush). Rush survived at Carrington near the inlet, but never flourished. Junipers appear to have good potential, but are showing mixed results. *Juniperus sabina* 'Broadmore' (Broadmore Juniper) and *J. procumbens* 'Nana' and *J. conferta* 'Blue Pacific' (Blue Pacific Juniper) all have excellent groupings, but each species has individuals that have died.Smaller trees that established well are *Chilopsis linearis* (Desert Willow) and *Acer ginnala* (Amur Maple). Shade trees have shown less consistent development across sites. *Platanus* cultivars 'Bloodgood' and 'Exclamation^{TM}' (Planetree) and *Betula nigra* 'Heritage' (River birch) have advanced in most gardens *Ulmus parvifolia* Allee cv. 'Emer II' has established well. *Pinus taeda* (Loblolly pine) has established in most gardens but has struggled to recover from ice storm damage.

Table 1. Plant species data for all project sites.

Scientific Name	Common	Media[1]	Year[s]	Health[2]	Survival[3]	Observations
Acer ginnala	Amur Maple	E	5+	VG	High	Limited attention needed
Artemisia 'Powis Castle'	Wormwood	E	5+	VG	High	Very expansive growth
Betula nigra	Riverbirch	S/E	5+	F	Medium	
Buxus sinica var. *insularis* 'Wintergreen'	Wintergreen Boxwood	S/E	5+	G	Medium	Irrigation may be necessary
Calyophus drummundianus var. *berlandieri*	Texas Primrose	S	2	G	Medium	
Cercis canadensis	Common Redbud	S/E	5+	G	Medium	Needs shade
Chilopsis linearis	Desert Willow	E	2	VG	High	Fast grower
Echinacea fulgida	Orange coneflower	E	2	G	Medium	
Euonymus japonicas 'Aureo-marginata'	Golden Euonymus	S	5+	G	High	
Hemerocallis 'Stella de Oro'	Stella Daylily	S/E	5+	VG	High	Dependable bloom
Hemerocallis spp.	Daylilies	S/E	5+	VG	High	Dependable bloom
Ilex spp.	American Holly	S	5+	G	Medium	
Ilex vomitoria	Yaupon Holly	S/E	5+	VG	High	
Itea virginica	Virginia Sweetspire	S	5+	N	-	
Juncus effusus	Rush	S/E	5+	S/N	Low	Can survive at wet locations
Juniperus conferta 'Blue Pacific'	Blue Pacific Juniper	E	2	F	Medium	
Juniperus procumbens 'Nana'	Dwarf garden Juniper	S/E	5+	G	Medium	
Juniperus sabina 'Broadmore'	Broadmore Juniper	E	2	G	Medium	
Liriope muscari	Big Blue Liriope	E	5+	VG	High	
Liriope spicata	Lilyturf	E	2	VG	High	Fills in, need some weeding
Lobelia siphilitica	Great Blue Lobelia	S	5+	F	Low	
Miscanthus sinensis	Maiden Hair Grass	S/E	5+	G	Medium	
Oenothera berlandieri	Mexican Primrose	E	2	F	Medium	Sporadic growth and bloom
Oenothera speciosa	Evening Primrose	E	2	F	Medium	Sporadic growth and bloom
Pennisetum alopecuroides	Dwarf Fountain Grass	S/E	5+	G/F	Medium	
Perovskia atriplicifolia	Russian Sage	S/E	5+	VG	High	Very expansive growth
Pinus taeda	Loblolly pine	S/E	5+	VG	Low	
Platanus 'Bloodgood'	Planetree Bloodgood	S/E	2	VG	Low	
Platanus 'ExclamationTM'	Planetree	S/E	2	VG	Low	
Rosa 'Knock out'	Knock out Rose	S/E	5+	VG	High	dependable bloom
Salvia greggii	Autumn Sage	S/E	2	VG	High	Very expansive growth
Schizachyrium scoparium	Little Bluestem	E	2	G	High	
Sedum acre 'Arabicus'	Stonecrop Sedum	E	2	S	Low	
Ulmus parvifolia Allee cv. 'Emer II'	Allee Elm	E	2	G	Low	
Verbena canadensis 'Homestead Purple'	Garden Verbena	E	2	S	Low	

[1] S = Sand, E = Expanded clay; [2] VG = Very good, G = Good, F = Fair, S = Struggling, N = Not present; [3] H = high (>85%), M = medium (84-50%), and L= low (<50%).

7 RECOMMENDED PLANT PALETTE OPTIONS

From the observations of performing species in Table 1, we offer two options for the combination of lead species for future dryland investigation and trials. Some of these pairings were observed in particular sites, yet individual species are suggested to provide a practicality (conventional trade palette) or thematic (lumina palette) (Figure 9 and 10). Both palettes possess the expression of the dry-windy environments of the south plains through tones of foliage, exfoliating bark, and flower size, shape, and color. The conventional includes more temperate color and texture aesthetics, while the lumina palette includes more arid texture and color aesthetics. This higher intensity light and resilience to environment phenomena can be used as defining themes in plant palette development.

Figure 9. A suggested 'conventional trade palette' where *Hemerocallis spp.* (Daylilies) (Left), and Rosa 'Knock out' (Knock out Rose) (Right) are used as leading organizers in texture, color, and seasonality. *Schizachyrium scoparium* (Little Bluestem) (Center left) offers and fine textural contrast with native seasonality in winter color while *Platanus* spp. (Planetree) (Center right) offers a exfoliating bark, open canopy, white light quality and dappled shade.

Figure 10. A suggested 'lumina palette' where *Perovskia atriplicioflia* (Russian Sage) (Left), *Artemisia* 'Powis Castle' (Wormwood) (Right). *Schizachyrium scoparium* (Little Bluestem) (Left center) provide a garden structure made of highly tinted foliage which is contrasts with the shaded tones of *Ilex vomitoria* (Yaupon Holly) (Center), and seasonal expressions like *Calyophus drummundianus* var. *berlandieri* (Texas Primrose) (Right center).

8 DISCUSSION

All projects have been monitored for their influence on stormwater runoff water quality. Deerfield Estates, Grove and Trailwoods are assessing runoff quantity. Because vegetation assists with nutrient retention (Lucas and Greenway, 2008) while providing important aesthetic and biological associations

(Kellert and Wilson 1995; Beatley 2011) the understanding of plant selection, health, and maintenance remains a priority.

Home owner LID buy-in and positive maintenance practices can determine the success of bioretention systems (Deitz et al. 2004). To that end, local education and stewardship occurred in all project locations, yet it is uncertain how effective those programs were at improving plant survival and health. At Trailwoods a Stewardship guide was created for the projects to educate and assist the homeowners with their bioretention gardens. These guides included everything from plant material used in the project to how to maintain the plant material throughout the seasons. Also within the guide is knowledge of the suspected unwanted plant material that is expected in the gardens and the best management practice to remove the plant material as well as the tools needed to assist in the removal. The guide has both text and pictures of the plant material, tools, and information of the project site. Additionally, stewardship workshops were scheduled throughout the project as well as individual meetings with the homeowners to discuss any questions and concerns with the maintenance of the gardens and any other plant material concerns within the property. One workshop was held in January of 2014, May of 2014, and a final workshop in September of 2014. One-on-one workshops were often held with the homeowners at Deerfield Estates throughout the year of 2014 to answer questions and demonstrate proper maintenance practices.

In some projects, warm season fertilization was observed in the lawn areas adjacent to the bioretention cells. In a few isolated cases, fertilization was observed in the rain gardens. The prevalence and the practice of using garden and lawn fertilization for plant establishment could be undermining water quality goals. If Deitz et al (2004) are correct then long standing behaviors (and practices) using conventional practices to establish and maintain healthy vegetation may create trade-offs in water quality performance when nutrients are added.

The selections of vegetation, by the various designers and constructors of the project showed a relative reliance on local nursery supply. Few selections were experimental species or varieties; instead the proposed designs were, in large part, examining the adaption of currently available materials. In mesococosom studies, Houdeshel et al. (2015) examined one shared species *Schizachyrium scoparium* (Little Bluestem) and an *Artemisia* species in upland conditions that showed net-export of NO_3. While the wetland treatment in their study performed better as nitrogen sink, they suggest increasing plant density in the upland setting for improve biogeochemistry, which may be influenced by the soil microbial community. However, their discussion was limited on plant diversity, productivity, growth and species health. Although only used in only the more recent project sites in our study, *S. scoparium* established quickly and individual plants exhibited high shoot growth in the first two seasons.

In the breadth and duration of this study, additional species were installed in projects and sites, but episodic record keeping prevented a comprehensive cataloging of all failed species. Therefore, the species listed here tended toward the clear survivors and a few species that repeatedly failed across several projects and sites. Of the most successful, *Ilex vomitoria* (Yaupon Holly) a native to Oklahoma, grows in both sandy as well as clay soils, but has shown to do well with enhanced good rooting conditions (Thetford et al 2015). Even though *I. vomitoria* tends to be successful in local soil conditions, the 36" depth of porous retention media may have offered a fitting rooting environment. It was used as an evergreen, as well as, a shrub for screening and massing across sites in sand and expanded clay mixes. *Acer ginnala* (Amur Maple) was not used often, but survived in nearly every recorded application and appeared in very good health when used. In two cases, it was one of the few plants that survived under near neglected maintenance, when other species failed. *Perovskia atriplicifolia* (Russian Sage) and *Artemisia* 'Powis Castle' (Wormwood) are both well-known drought tolerant selections. P. *atriplicifolia* showed consistent and long duration bloom and dramatic establishment. In one project site, in which maintenance was provide by the research team during establishment, *P. atriplicifolia* new shoot growth was selectively removed from in areas where it was encroaching other species masses. These same plants experienced canopy growth into the street and sidewalk requiring tip pruning at the request of city officials. *Hemerocallis spp.* (Daylilies), including different forms of *H.* 'Stella de Oro', exhibited dependable survival, full foliage, and respectable bloom. It was observed to persist after the first season during severe climatic conditions without irrigation with only reduced foliage and bloom. Native *Salvia greggi* (Autumn Sage) exhibited an unexpected growth and health in several locations. Like the *P. atriplicifolia* its plant mass filled out to the size of a small shrub in which canopies grew across curbs providing every indication of strong native performer that offers long season blooms and massing.

The species lacking survival also tended towards nursery available species that were recommended in rain garden lists or adapted to wet settings, Houdeshel et al. (2015) illustrates that wetlands plants can be used in desert bioretention when hydric water regimes can be created thus providing an environment where species, such as *Juncus effusus* can establish and survive. Because the bioretention systems were designed with highly porous materials the failure of *J.effusus* and *Itea virginica* was likely due to poorly matched hydric regimes of the gardens, that were further stressed under the period of drought. Using *Juncus* spp., *Itea*, spp. or similar hydrophilic vegetation requires the design of more intentional inundation periods that was not planned for in the projects and sites in this study.

The use of NDVI proved informative. Although, limited by its one-time data capture in this study, it provided insight into how plants contribute to the performance of urban bioretention systems. Kovachich et al. (2011) used NDVI to determine water regime impacts in green roofs planted with dry adapted plants, showing it has potential in urban green infrastructure applications and may offer designers, researchers and maintenance personnel quick feedback on the performance of the vegetation. We found it ways to use and the model to be dependable, transportable and helpful in observing and communicating the conditions of the sites.

Although limited to issues in the visual spectrum, NDVI provided a quantitative indicator of plant growth, health, and ecosystem performance. We found small, but marginal differences in the flowers, grasses and small shrubs of the bioretention gardens when compared to the turf grass lawn. While both systems require pruning and maintenance, creating an exportation of biomass, the resident biomass in the rain garden was higher. Because suburban bioretention is replacing turf grass areas the bioretention vegetation is creating net ecosystem function for the neighborhood, when compared to lawns. These measurements may have other localized interpretations when managing watershed nutrient budgets. Currently, NDVI is used to diagnose and prescribe nutrient applications in crops (Guo et. al 2008), and it is possible that future further examination could be linked to nutrient budgeting in bioretention, providing quicker and affordable ways to evaluate nutrient biogeochemistry in green infrastructure. Affordable handheld models are now market available (Govaerts and Verhulst 2015).

The sampling population of 56 matched pairs provides a limited “point-in-time” indication of vegetative health and performance, Because NDVI is a spectral range measurement it is sensitive to soil effects. In this study the site-based measurements could have been influenced by the soil surface color of the two treatments: rain garden (topsoil/expanded clay) and tree lawn (local oxide clays). However, using hand held devices does control for other NDVI limitations: cloud, atmospheric and spectral effects. Commonly, satellite NDVI is recommended to be coupled with site-based sampling, such as LAI, CO_2 flux or biomass to provide improved validity in productivity measurements (Gamon et al. 1995). The reason to employ site-based recordings is to overcome the inaccuracy of omitting non-photosynthetic biomass (woody material), known as canopy structural effects. Fortunately, the garden possessed large percentages of herbaceous material and only young woody plants. Another advantage of hand held NDVI is that the bioretention gardens are like agricultural and horticultural settings, in which they a have more uniform conditions than natural ecosystems and offer an alternative when representative destructive sampling is unrealistic. Box et al. (1988) explain NDVI’s positive correlation with NPP and GPP and it has been shown to indicate in ornamental plant health (leaf nitrogen) (Dunn et al. 2015[1]; Dunn et al. 2015[2]). These advantages are improving popularity of hand held NDVI (Verhulst et al. 2011; Dunn et al. 2015).

Although, biomass and soil nutrient sampling would provide additional ground truthing it would also require additional collection, assessment and analysis by trained professionals. Assessing the NVDI of plant palettes would provide a group level assessment that could be comparative across projects. We recommend, future studies exam the relationships between NDVI and site-based measurements of biomass, LAI, CO_2 flux and other ecosystem function indicators to aid in the understanding of how vegetation contributes to bioretention systems performance.

9 CONCLUSIONS

In a multi-project study that was spatial distributed in the State of Oklahoma, we observed dry adaptive vegetation establishing and surviving within dryland bioretention systems created by decadal drought conditions. A field inventory showed high rates of survival and health in seven species during a dry climatic period: Ilex vomitoria (Yaupon Holly), Acer ginnala (Amur Maple), Perovskia atriplicifolia (Russian Sage), Hemerocallis spp. (Daylilies), Artemisia ‘Powis Castle’ (Wormwood), Salvia greggi

(Autumn Sage), and Schizachyrium scoparium (Little Bluestem). While mesic-hydric adaptive growers of Itea virginica (Virginia Sweetspire), and Juncus effusus (Rush) had limited survival and poor health.
In a comparative sub-study, a street right-of-way bioretention system (0.48) was more productive than traditional tree lawn landscape (0.38) as recorded with in-field Normalized Differential Vegetation Index (NDVI) recordings $t(55) = 3.38$, $p < .001$),. This is positive indication for the future use of NDVI as an affordable and non-destructive measurement of vegetative contribution to bioretention performance.

From these findings dry adaptive plants have can be considered for bioretention systems. Two small plant palettes provide lead options for building vegetative combinations that can establish in dry climates. These findings and methods can assist designers and researchers in Oklahoma, the Great Plains and settings that experience dryland conditions.

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