Contract No: 10-BC-28-12-00-22-008

Task 2 (b), (c)

Final Report: Fiscal Year 2011 – 2012

Comprehensive Wind Uplift Study of Modular and Built-in-Place Green Roof Systems
UF Project ID #: 95620

Submitted to:

Florida Building Commission
Florida Department of Business and Professional Regulation
Building Codes and Standards Office
2555 Shumard Oak Blvd.
Tallahassee, Florida 32399

Prepared by:

David O. Prevatt, Ph.D.
Principal Investigator
Assistant Professor, Eng. School Sustain. Infra. & Environ., UF

Report No. UF01-12
15 June 2012

Glenn A. Acomb, FASLA
(Dept. of Landscape Architecture, UF)

Forrest J. Masters, Ph.D.
Assistant Professor, Eng. School Sustain. Infra. & Environ., UF

Graduate Student: Tuan D. Vo
Research Assistant: Nickolas K. Schild

Department of Civil and Coastal Engineering (Structures Group)
Engineering School of Sustainable Infrastructure and the Environment
University of Florida
365 Weil Hall
P.O. Box 116580
Gainesville, FL 32611-6580

FOREWORD

The material presented in this research report has been prepared in accordance with recognized engineering principles. This report should not be used without first securing competent advice with respect to its suitability for any given application. The publication of the material contained herein does not represent or warrant on the part of the University of Florida or any other person named herein, that this information is suitable for any general or particular use or promises freedom from infringement of any patent or patents. Anyone making use of this information assumes all liability for such use.

DISCLAIMER

Results should be considered preliminary. They are provided for the express purpose of documenting the progress made on the project during FY 2011-12. The authors anticipate releasing final results to the Hurricane Research Advisory Committee or Soffit Workgroup.

TABLE OF CONTENTS

EXECUTIVE SUMMARY

The percentage of green roofs in the state of Florida is well below the national average, despite growing interest from green roof manufacturers and building owners. There is a reluctance to expand the market because our knowledge on how vegetative roofs would perform in hurricane wind conditions is limited. Green roofs in Florida must also contend with Florida's sub-tropical climate, which poses unique challenges to maintain plants through extreme hot, dry, and sometimes humid, and rainy weather.

In this report we have synthesized available knowledge on green roofs to identify the knowledge gaps. We report on the full-scale experiments conducted to evaluate how modular tray green roof systems and built-in-place green roof systems behave in simulated extreme winds. This first of its kind study presents data showing the effects of parapets or no parapet, module tray weight, and wind azimuth on plant performance. The results provide evidence in support of previously suspected but unconfirmed behavior of green roofs.

The response to the contract deliverables are summarized below, followed by specific recommendations. Design guideline recommendations are then presented. The recommendations and design guidelines are supported by the detailed report of activities (literature search and new research) that make up the bulk of this document.

Deliverables

Tasks 2(b) and 2(c) of the research encompassed the full-scale wind uplift tests of module tray and built-in-place green roof systems. The study was designed to establish a basic understanding of the performance of the roofing systems, the plant materials and growth media, within the context of an approximately 12-month exposure to North-Central Florida weather. The following is a summary of the activities and findings referenced to contract task number.

- *Recent Research on Vegetative Roofing Systems in the Public Domain*: Our Final Report for Task 2(a): "State of Knowledge of Green Roofs in Florida," Report No. UF04-11, dated 23 September 2011 summarized the state of knowledge available in the literature. This document identified the constraints to growing green roofs in Florida and uncertainties regarding plant selection for hot, humid sub-tropical climates. The report underscored the many incentives for building more energy-efficient buildings, reducing heat island effects and utilizing water retention capabilities of green roofs that would make this construction attractive. The Florida Building Commission directive specifying all roofing components should have product approval standards, has limited the installation of green roofs since no accepted standard for wind uplift testing exists.

- *Preliminary Understanding of Performance of Vegetative Roof Systems*: Task 2(b) describes the methodology and provides results of Phase I testing in our report titled, "Wind Performance Study for Extensive and Intensive Green Roof Modules, Report No. UF03-11," dated 23 September 2011. Tests were conducted on a modular tray green roof system for two growth media depths of 4 in and 8 in. A mock-up roof structure was built that included a 12 in tall parapet. Six selected plants were used in each module tray, consisting of a mixture of tall and low-growing varieties. Reverse airflow along the leeward parapet caused most extensive erosion and scour of the growing media in unprotected modules. The plant coverage significantly reduces the extent of this scour action. Plant vigor, as expected is enhanced in the 8 in deep (intensive) module trays, but both the 4 in. and 8 in. deep systems grew well during the trials.

- *Parametric Study to Measure Effect of Hurricane Winds on Green Roofs*: Phase II testing, contained in this report, "Comprehensive Wind Uplift Study of Modular and Built-in-Place Green Roof Systems," Report No. UF 01-12, dated 30 June 2012, sets out results of wind uplift tests, root resistance tests to quantify the extreme effects of simulated extreme wind, and heavy rainfall on the roof systems. New test procedures were developed to measure plant performance in Chapter 6 (herein), including a root uplift resistance device. Wind testing conducted using UF's Hurricane Simulator showed the critical role that cornering wind vortices play in damaging green roofs and erosion of growing media. In addition, roofs without parapets will likely experience the highest suctions that require corner and edge green roof systems to be securely tied to the structure to prevent failure.

- *Existing Design Guidelines for Green Roofing Systems*: Report No. UF01-12, provides an analysis and comparison of the design guidelines for vegetative roofing systems in use in Europe (the FLL document), and the United States (Factory Mutual's FM 1-35, ANSI/SPRI's RP-14, and VF-1). FM1-35 presents the most conservative design approach that would exclude green roofs from being installed in most areas of Florida. While fire resistance considerations in VF-1 were beyond the scope of this research, comments are provided since plants go dormant and die-back during the dry winter months in Florida. Maintenance of the green roof system is an important parameter to be considered.

- *ASTM Green Roof Task Groups, E60 and D08*: At present, the Green Roof Task Group E60.01.07 of the American Society of Testing and Materials' E60 - Sustainability Committee is tasked to develop a consensus-based guideline for vegetative roofing systems. Dr. Prevatt presented preliminary results of this research to that Task Group's April 2011 meeting. Michael Gibbons, Chair of this Task Group has agreed to allow his task group to review this report and provide comment and feedback on its content and conclusions. ASTM has already developed several test standards related to green roof systems, under the E60 committee as well as under the D08 committee. The result of this Task Group's work will be a document that identifies the terminology, principles and fundamental concepts for green roof systems including sustainability, technical requirements of construction, and types of vegetated vegetative (green) roof systems used on buildings. The D08 Task Group has the focus on the properties of roofing/ waterproofing membrane systems specifically for vegetative (green) roof systems. ASTM as yet does not have a wind loading task group and the collaboration with the University of Florida Investigators will be developed further.

Specific Recommendations

The Investigators recommend the adoption of a state-wide green roof wind uplift design guide for application to green roof systems in Florida. The following should be addressed: 1) a standard test procedure for evaluating the wind resistance of the roofing system, 2) guidance for selecting Florida-appropriate plant materials, growth media mix and media depths, and 3) stipulation of minimum building considerations for parapet/gravel stop heights, anchorage methods and assembly of green roofs, particularly in corner and perimeter roof zones.

The Florida green roof design guide should leverage the work in existing design guides for green roof systems that were reviewed in this report, such as the recently approved RP-14 and FM 1-35, and the European design guide, the FLL. The Ballast Design Guide, TechNote 508.1 by Dow Chemical was also an important reference for green roof design documents.

The FM 1-35 document refers to Factory Mutual's well-established wind design procedures, 1-28 for the design of flat or low-sloped commercial roofing systems. As a result of this, the 1-35 provisions are very conservative, limiting the use of green roof systems to regions where the design wind speed is less than or equal to 100 mph. 1-35 also restricts the use of green roof from the edge and corner zones of the roof. While these provisions may one day be found to be necessary, without the benefit of experimental data, the justification of such constraints was not obvious to the Investigators.

The Investigators believe the consensus-standard development process for green roofs that are underway through the American Society for Testing and Materials (ASTM) will soon yield another document for guidance. Current ASTM documents pertaining to green roofs are discussed.

While the development of these design guides are beneficial, the Investigators observed and identified discrepancies among them. There were some omissions of details considered pertinent to the sub-tropical climate that should be developed as part of any green roof guide for Florida. Ultimately, the limitations of the current design guides are their lack of experimental or empirical models of wind uplift performance of green roof systems. This has been partially addressed in this report.

The Investigators are committed to disseminating the research results by seeking commentary from the ASTM E60.01.07 Green Roof Task Group at their next meeting, and through direct collaboration with manufacturers, landscape architects and other interested parties. To that end, the Investigators submitted an abstract which was accepted for presenting a session of wind uplift testing of green roofing systems at the "CitiesAlive" Conference to be held in Chicago in October 2012, and which is sponsored by Green Roofs for Healthy Cities.

Finally, the selection of plants for green roof systems in Florida requires the evaluation of a wide range of important characteristics of building/roof, green roof assembly technology, plants, and the variables of climate across the State. While our research has addressed many of the issues in plant performance in high wind, a compilation of a plant list is not made herein. However, our outline guide presents our assessment of suitable characteristics that emerged from our study.

Wind Uplift Design Guideline

It is the recommendation of the Investigators that a single authoritative document should be built through the normal consensus process of the Florida Building Commission in order to eliminate some of the uncertainty in constructing sustainable green roof systems in the Florida climate. While this was the original intent of the research, the experimental research had to be focused on fundamental understanding of failure mechanisms of the green roof systems.

A proposed format for a design guide is recommended to follow the three factor approach taken by the FLL:

1. climate/weather dependent factors
2. structure/building dependent factors
3. plant-specific factors (Table 4 and Section 4.1.1).

RECOMMENDED GREEN ROOF DESIGN GUIDELINE ISSUES FOR WIND UPLIFT/FLORIDA BUILDING COMMISSION

The Investigators recommend the adoption of a state-wide green roof wind uplift design guide for application to extensive green roof systems adoption in Florida. As yet, no one existing design guide provides all the needs for the green roof development in the state. The Green Roof Design Guide should include the following: 1) a standard test procedure for evaluating the wind resistance of the roofing system, 2) guidance for selecting Florida-appropriate plant materials, growth media mix and media depths, and 3) stipulation of minimum building considerations for parapet/gravel stop heights, anchorage methods and assembly of green roofs, particularly in corner and perimeter roof zones.

Adopt the Checklist of the FLL Design Guide

Any Florida green roof design guide should use a proposed format of the FLL that presents a three-factor approach with the following checklists: 1) climate/weather dependent factors; 2) structure/building dependent factors; and 3) plant-specific factors (Table 4 and Section 4.1.1).

Adopt RP-14 Standard

The ANSI RP-14 represents a good standard, but for Florida applications it has several limitations that should be addressed (within the FBC document):

1. RP-14 has very limited information regarding plants and the characteristics that affect wind uplift. The additional information contained in this report will aid in enhancing successful applications in Florida.

2. Paragraph 2.3.1 addresses a maximum of 5” of exposed growth media, but it is not clear if this evaluation is to be made at the time of planting or later as plants grow. In the industry, it is common to plant smaller plants at the desired spacing in order to allow the plants to grow and achieve coverage. This is done for reasons of cost and because smaller, younger plants are often more resilient and better able to adapt to the extremes of the roof. Therefore, if held to this standard at the time of planting, the cost of newly planted roofs will increase significantly. The UF testing revealed that green roof trial plantings took only two months to achieved necessary coverage (easily meeting the 5” requirement) and were planted at typical spacing of young plants.

3. In Cl. 2.3.1, it is not clear how the measurement of the 5” exposed growth media is determined. Plants that are commonly used in green roofs in many other (colder) climates in the United States utilize sedums, an alpine plant species that is very short (approximately 4”-6” in height) and grows in a dense compact form. However, green roofs in Florida, as well as an increasing amount of green roofs in other regions, are utilizing other plant species such as native plants, ornamental plants, and grasses that have forms that overhang the base of the plant. This overhang covers the growth media if viewed from above the plant, but has some exposed growth media if one views the plant from a 45° angle. In addition, other plants grow with above-ground rhizomes (stems) and foliage that lie on the top of and cover the growth media. In high winds,

the rhizome can be lifted up, exposing the media and scour a limited amount of media. How would this be measured to assess the 5”? Would the cover of the rhizome with foliage lying on the ground meet the 5” requirement?

4. C.1.0 defines extensive as growing media depths less than 6” and intensive depths as greater than 6”. What term will apply to 6” growing media depths? Later in this Section, there is reference to “large shrubs and trees” as needing attention to ensure “adequate anchorage and structural support” is given. However, there is no definition of a “shrub” to distinguish it from other small green roof plants (typically known as groundcovers or shrubs), nor is there an explanation or definition of anchorage and structural support. This can be confusing.

5. C.2.6 does not explain “woody” vegetation that is to be minimized to avoid becoming airborne debris. There are a variety of small plants whose branching structure is difficult to ascertain if it is woody or soft. Further, at what point is a very small woody branch a risk to building damage if airborne?

Adopt VF-1 Standard

There are fire implications in Florida, especially in the dry seasons of fall and spring, and for locations listed as “fire-prone” by the State of Florida Forest Service.

The ANSI VF-1 represents a good standard, but for Florida applications has several limitations that should be addressed (within the FBC document):

1. In Section 2.0 “Definitions” and 4.1 “Vegetative Roof Design Options”, there is no reference to a “woody” plant. Only succulents and grasses are listed. For Florida, this omits a large number of suitable plants to be considered for a green roof.

2. In Commentary Section C5.0, “Maintenance”, it is recommended that the “Removal of dead foliage should occur on a regular interval, for most roofs and that may be at least once a month.” The term “dead foliage” is general and could be widely interpreted. Is any dead foliage an issue, or is the majority of a plant’s foliage the concern?

Plant and Florida Green Roofs

Selecting plants that are suitable for a green roof’s challenging environment requires specialized knowledge of plants, technology and environment. On one hand, the selected plants must possess certain physical characteristics (form and root system), ability to handle extreme heat, possess vigorous growth, seasonal attributes, regenerative capacity, and limited maintenance needs. This knowledge must be assimilated with that of the roof design and its green roof assembly format, as well as wind dynamics, direct and reflected radiation, growth media characteristics, and assembly maintenance needs. Finally, selected plants must be adapted to the local climate (hardiness zones), extreme heat, seasonally heavy rainfall, humidity, frost/freeze dynamics, seasonal periods of drought and extreme events of hurricanes and fire.

For many parts of the nation, plant selection for green roofs heavily favors the sedum family and other succulents plants due to their capacity to balance cold and dry conditions, retain moisture for future use and limit transpiration in times of drought. This is achieved through a process known as "crassulacean acid metabolism" (CAM), possessed by sedums and a limited number of succulents that have characteristics similar to CAM, although to a more limited extent.

Sedums, however, are alpine plants and are genetically disposed to prefer cold, dry climates and are not typically adapted to humidity nor to competition from other plants. With Florida's hot, humid climate (encompassing USDA Hardiness Zones 8, 9 and 10) and a wide variety of weeds and other forms of competition, sedums and other succulents have been thought to have very limited potential without field testing to be certain how a succulent can be cultivated.

Particularly problematic are Florida's summer temperatures. Surface temperatures of exposed green roof media have been found to reach 165° F[1], with little cooling through the night. Combine this with ever-present humidity and seasonally heavy rainfall, and few plants will thrive without careful selection and a green roof assembly design that meets plants' needs, including irrigation to survive the dry months.

Since Florida's first green roof (2003) and others since that time, the majority of roofs in Florida have relied on plant choices favoring native and ornamental plants adapted to the Florida climate, and provided irrigation (typically low-volume or drip) to deliver nutrients and mitigation for heat and drought.

Research of plant species for green roof applications was established at the University of Florida with the design and installation of the Charles Perry Construction Yard Green Roof in 2006-2007, and was expanded through field trials in 2009. The purpose of this work is to explore suitable plant selections cultivated in extensive green roof growth media and assembly conditions. The majority of these characteristics are measured or observed, and they constitute a useful list of characteristics that can guide plant selection for Florida green roofs:

- *Tolerance of heat and drought over time*. (daily, weekly, and seasonally)
- *Tolerance of the water balance within the green roof assembly*
- *Perennials should dominate the design* (die-back results in biomass fuel and/or vacant spaces or exposed growth media)
- *Habit of plant and its root systems* (dimensions, type, and density)
- *Compatibility with other plants* (to allow co-existence and limit competition)
- *Tolerance of cold temperatures* (observe freeze damage and resulting biomass)
- *Resistance to disease and weed competition*

Wind Uplift Plant Selection Guidelines for Green Roofs

Florida's unique range of seasonal climate extremes presents unique challenges to plant selection for green roofs. High heat and drought, as well as periods of heavy rain and humidity require

[1] Field trials at the University of Florida have found daytime summer temperatures of dry conventional growth media to be as high as 165°F.

plants (and the assembly design of the green roof) to handle a range of extremes. While each green roof will have unique context, micro-climate, exposure, roof design, wind exposure and other related characteristics, there is a series of selection criteria that can be followed, informed by standards by FLL, ANSI, ASTM and other sources.

This list of design guidelines for plant selection is prepared with a focus on wind uplift. It follows a sequence of decisions in a general hierarchy, although there may be circumstances that require shifting of the order.

1. Hardiness for Heat and Drought

Coping with seasonal variations of heat and drought is the greatest challenge for plant survival in Florida, and this is further complicated by the extremes of a green roof environment. The entire plant palette for a green roof should be selected on a basis of the capacity to survive in heat and extended droughts. While irrigation can be a mitigating factor to suppress high temperatures in dry months, the use of this valuable resource should not be taken lightly, forcing plants to survive on a roof without constant use of water. Where possible, the design of the green roof and the arrangement of plants can allow for some shade – from a taller plant to a shorter one, or in the insertion of features in the design such as vertical elements, perches, etc.

2. Plant Types

Plants for green roofs should be selected from perennials, succulent, grasses and annuals in order to provide diversity – both visual interest and biodiversity.

- *Perennials*
  Perennials, sometimes referred to as evergreens, are herbaceous plants that remain healthy throughout the year. As a healthy viable plant, they should be the dominant plant type so that the green roof possesses attributes of hardiness, wind uplift resistance, resisting fire, and useful in suppressing weeds. Perennials, including succulents should be a minimum of 60%-70% of the planted cover of a green roof. Perennials can be ornamental or native species, although there are few natives that are perennials and capable of thriving in an extensive roof's growing media. Succulents will be discussed in a subsequent heading.

- *Annuals*
  Annuals are plants that die after a year or a growing season. While useful as a flowering ornamental or native plant that can reseed each season, the annual plant that is declining at the end of its season or has "dead wood," presents concerns of aiding fire and wind uplift susceptibility. In order to comply with ANSI VF-1, enhanced maintenance will be required to remove dead biomass when plants or flowers are spent, and be alert to exposed media larger than 5" (ANSI RF-14), that results from the plants that have expired and exposed media. Annuals should be limited in the overall percentage of planted cover of a green roof to no more than 30%.

- *Succulents*
  While succulents are perennials, they are listed in this special category due to their valuable qualities of drought tolerance, cold tolerance, wind uplift suppression (low profile) and resisting fire. As presented earlier, a number of succulents (Sedums and Delosperma) possess CAM qualities of storing water and limiting transpiration in droughts. As such, they can exist much longer with very limited water, and their retention of water will retard fire. These should be contained within the annual perennials percentage above.

- *Grasses*
  Grasses are also ornamental and native perennials, too, but can retain spent blooms or leafs at the end of a growing season. The designer should be alert to the existence and removal of biomass to satisfy ANSI VF-1. Root systems are often dense and fibrous, which contributes to limiting the force of withdrawing a plant in wind uplift. Those grasses that are perennials should be counted in the percentage of planted cover of a green roof, while those that are semi-annual or annuals should be contained in the annual percentage listed above.

- *Woody Plants*
  Though not a specific category of plant, references are made about the use of woody plants in green roofs and are included in this list. Woody plants tend to be larger in size, possess stems, branches and root systems that are "wood-like", and can be shrubs or groundcovers. They can be a perennial or an annual. Their stem strength and vigorous root systems are useful in resisting wind uplift (ANSI RP-14), although if an annual plant, there will be the need to attentive to the removal of biomass (ANSI VF-1). However, being wood-like, they can be more susceptible as fuel for fire (VF-1).

3. Plant and Root System Morphology (limited to the species/families tested)

The plant morphology, especially its characteristics of stem, rhizome and roots, are important to be understood as they affect the ability of plants to derive nutrients from the media, the functional effectiveness of the growth media, and integrity of the waterproofing layer. They are addressed in FLL Standards.

The characteristics of a plant's root system and its morphology at various ages should be known before a plant is selected for a green roof. Important criteria include depth of roots, the quantity of roots, and the density of the tissue of the roots. Roots will provide nutrients to the plant, the stability to withstand wind uplift, and to interconnect with other roots to resist other plants wind uplift. On the other hand, deep running roots ("tap roots") that are strong and woody should be avoided as they afford the potential to damage the waterproofing layer. Also, above-ground rhizomes that initiate roots at each joint of the rhizome (as short as every 1" or 1 ½") can be an indicator of an aggressive root system and a maintenance concern.

Avoid excessively fast growing plants, aggressive rhizomes, and plants that are listed on any invasive list. The green roof planting design should match plants that will not compete with one another for nutrients and moisture.

4. Plant Origin

The origin of plants to be used in a green roof should be investigated to insure health and success. Native and ornamental plants become genetically adapted to their origins over time and will prefer to respond to that climate, seasonal changes, and nutrient availability. For this reason, when selecting the plants for a green roof, the origins should be investigated, whether raised from seed or cutting. The mere specification of genus and species is not sufficient for any plant that is widespread throughout a state or region.

There are other environmental conditions necessary to investigate before selecting plants:

- the seed source
- growth media used by the nursery
- irrigation practices
- fertilizer practices

Because plants will be placed on a roof after being raised in a nursery, the first few days and weeks are crucial to their success. If the plants have been treated dramatically different than what will be encountered on the roof, there is a good chance that the plants will shock or expire. Even if they do live, the recovery period will take time.

For these reasons, the industry has seen the emergence of pre-grown vegetated in the modular trays to allow plants to adjust to these conditions. However, there is a cost to “raising” the plants in a nursery and for the time this is done, which elevates this product over the cost of a built-in-place green roof. It is, however, a viable consideration for any green roof that has unusual or harsh conditions that would cause concern for success.

5. Plant Form and Leaf Area

Plant form and leaf area are often considered to be key determinants in wind uplift. However, in extensive green roofs, these characteristics are less significant because plants that are suitable for extensive green roofs tend to be small (under approximately 30-36 inches), flexible, have smaller leaf size and tend to interact with each other to form an integrated unit.

- Upright plants, as long as their leaf size is not excessive and subject to wind uplift, tend to be flexible. Their flexibility is exhibited in our wind uplift tests.

- Horizontal plants, i.e., plants that grow in a low, surface-hugging form, are very useful in a green roof planting because they assist in covering and protecting growth media from being scoured or uplifted. This is exhibited in our wind uplift tests.

- Mixed plantings are useful in green roof planting design because a variety of plants and plant forms can integrate and co-exist with one another, and provide limited wind uplift opportunity.

6. Plant Age and Coverage (in the green roof assembly)

Due to Florida's sub-tropical climate, plants grow more rapidly than in other parts of the country. The age of plants has proven to be a minor concern in the UF tests. Plants were tested at various ages of installation in the green roof assembly planting: two months, six months and 12 months. The 2 month-old, built-in-place planted assemblies proved remarkable in their speed to achieve coverage of growth media, and in resisting wind uplift. Their foliage proved flexible in high winds, bent and resisted breaking. In addition, the young root systems proved to be strong enough to resist wind uplift (Chapter 6 of this document).

7. Plant Health and Maintenance

In addition to careful plant selection, regular observation and maintenance are essential for ensuring an ongoing and successful green roof. As living organisms, there can be a variety of issues that arise over time to affect plant health, and adjustment to the growth media. Selecting plants that have few pests and diseases is essential. Also important is the maintaining of conditions that provide for a healthy plant.

A key in the planting, design and arrangement is the matching of plants that require common conditions such as growth media composition and moisture. In this way, the growth media can be altered to meet plant needs and the irrigation system can provide the amount and frequency of water essential for survival and good health.

It is necessary to plan a regular visitation by a professional to inspect the plant health, growth, and identify concerns and diseases/pests. In particular for Florida, weeds are a common occurrence and it will be necessary for them to be removed as soon as possible before a large colony is established. Another task for this visit is pruning or removal of unkempt plants, removal of dead bloom or seed heads, and removal of dead plants. ANSI VF-1 requires a minimum of 2 visits per year, and more will be needed depending upon the amount of annuals or plants that are under some form of stress.

Finally, general maintenance may be needed in a green roof that has high visibility to the public and for which there is pressure for the owner to have a certain appearance.

8. Irrigation

Due to Florida's extremes of temperature and extended drought periods, irrigation is useful to combat plant problems in periods of drought and high heat, and to limit the risk of fire. It is possible to consider a green roof in Florida without permanent irrigation, but the plant choices and appearance will be limited when the plants endure long periods of drought or high heat. If a green roof was not publicly visible, it would be more reasonable to consider a temporary or manual irrigation system.

When using irrigation, it is important to address the chemistry of the backup water source. Reclaimed water is a popular and sustainable source of backup water when lack of sufficient rainfall has depleted the level of the cisterns. Depending upon the level of treatment by the local utility, it is likely that there will be elevated levels of nitrogen and phosphorus, and these can fuel ornamental and weed plant growth. Native plants and succulents need modest levels of nutrients and these are reasonably available in growth media.

The remainder of this document discusses the objectives, background and details of the research conducted under this contract in support of the recommendations and guidelines provided above.

OBJECTIVE

Task 2: Investigate the performance of vegetative roof systems appropriate to Florida building for performance in hurricane wind and rain conditions. The contractor is authorized to spend up to $56,801 for Task 2(a) and 2(b).

(a) Capture and present the most recent research on vegetative roofs in the public domain. Catalogue and compare the availability of multiple vegetative roof systems, their anchorage to the roof structures and installation and design criteria. Report on test methods and results (if any) of wind uplift tests on vegetative roof systems. Identify current gaps in knowledge of the behavior of the systems in hurricane conditions and to propose future research to address the unknowns. Provide a report on the research information collected with analyses and recommendations.

(b) In Phase I of the study conduct full scale module tests to develop a preliminary understanding of the performance of vegetative roof systems in high winds. Vegetative roof systems will be "typical Florida-appropriate" systems. Tests will evaluate at a minimum biomass loss, scouring characteristics and plant damage for moderate, strong and extreme winds and with torrential rain. Tests will be designed to evaluate rate of recovery of vegetation and the effect of multiple storms on the vegetative roof systems.

(c) In Phase II of the study parametric studies to measure the effect of hurricane force winds on uproot resistance and plant breakage strength of plants used in vegetative roof systems will be conducted and draft proposed test standards will be developed. The parametric studies will also evaluate growth media scour resistance for uplift pressures and wind speeds and determine an acceptable level of material loss and vegetation damage for green roof systems. Recovery times for test specimens after testing will also be evaluated. The contractor will develop a standardized test procedure for evaluating green roofs hurricane wind related performance in Phase II and will submit the procedure to ASTM and the Green Roof Council for initiation of national consensus standards development. The contractor shall present study results in peer reviewed journals. The contractor is authorized to spend up to $25,000 for initiation of Phase II to include the design and construction of test samples with sufficient time provided for full growth establishment of the vegetative roof system samples selected. Testing will proceed upon appropriation funds for fiscal year 2011-2012 and modification of this contract.

THIS PAGE IS LEFT BLANK INTENTIONALLY

1 BACKGROUND

Interest continues to grow in the United States on utilizing green roofs as a sustainable method for construction of roofing systems. Extensive literature has shown that green roofs can:

- Reduce storm-water runoff rates during rainfall events (Alfredo, et al., 2010, DeNardo, et al., 2003, Getter, et al., 2007, Nagase and Dunnett, 2012)
- Improve the water quality of the runoff (Long, et al., 2007, Long, et al., 2008, Long, et al., 2008)
- Reduce the urban heat island effect in cities (Teemusk and Mander, 2010, Alexandri and Jones, 2008, Susca, et al., 2011)
- Decrease cooling and heating loads in the building envelope (Figueroa and Schiler, 2009, La Roche, 2006, La Roche, 2009, Sonne, 2006, Castleton, et al., 2010)
- Improve air quality (Li, et al., 2010, Yang, et al., 2008)
- Reduce sound pollution (Connelly and Hodgson, 2008, Van Renterghem and Botteldooren, 2008, Van Renterghem and Botteldooren, 2009, Van Renterghem and Botteldooren, 2011, Yang, et al., 2012)

However, the literature review conducted in 2010 (Prevatt, et al., 2011) exposed an obvious lack in wind and plant-species performance research for green roof systems in subtropical and tropical climate regions. For this reason, the green roof industry in Florida has lagged behind despite the high potential for the state to experience those cited benefits.

For this reason, the Florida Building Commission (FBC) tasked the investigators at the University of Florida to conduct an extensive literature review on existing green roof research (as mentioned above), perform full-scale wind performance studies on various systems, and conduct parametric studies which would all direct a wind testing standard for green roof systems.

1.1 Report structure

The following document will summarize the two-year study conducted by the University of Florida on the wind performance and plant design/selection of green roof systems in Florida in accordance to the tasks assigned by the Florida Building Commission. This report will:

1. Supply a comprehensive literature review of green roof research conducted in 2010 as a separate document.
2. Provide an extensive literature review exploring existing wind engineering studies conducted on flat roofs, parapets, gravel, and pavers, and also wind failure studies on plants/crops in Section 2. This literature review will form the support behind design considerations for Phase 2 of testing.
3. Present and summarize any existing wind performance studies on green roof systems in Section 3. The section will highlight any limitations recognized by the authors of this report for scrutiny and/or further research.
4. Highlight similarities and summarize the methodology behind existing green roof design guidelines. Focus of this in Section 4 will be on wind design and plant selection.
5. Discuss the biomass losses and scour characteristics involved with both phases of wind testing in Section 5.

6. Explore the plant performance due to extreme loads, media depth, age of establishment, growing season, and plant species (Section 6). Further experiments will aim to quantify and relate the extreme loads to existing hurricane simulator results through root uplift tests.
7. Formulate standard and proposed test methods based on results found and observations made by investigators. Standard test methods will be submitted to the American Society of Testing and Materials (ASTM) and the Green Building Council. The bulk of this report will be reviewed, edited, and submitted as a peer-reviewed journal article and conference paper.

2 WIND ENGINEERING LITERATURE REVIEW

Following the 2010 green roof literature review (submitted as a separate document) and the first phase of modular tray green roof wind studies, the investigators were interested in identifying a relationship between green roof systems and existing wind engineering research. With a defined relationship, the knowledge gap in green roof wind performance could be filled with existing wind engineering studies. This review was also motivated by the references cited in the wind design standard set forth by the American National Standards Institute (ANSI) and Single Ply Roofing Industry (SPRI), ANSI/SPRI RP-14: Wind Design Standard for Vegetative Roofing Systems. This design standard (and others) will be discussed in Section 3 of this report. This section and presiding subsections will summarize the review of wind engineering literature on flat roofs, and roofing components and plant structures at ground level. The remainder of the report will reference back to portions of Section 2 when relevant.

2.1 Wind Flow Effects over Flat Roofs on Low-rise Buildings

Extensive wind tunnel and full scale studies have been performed on boundary layer wind flow around box-shaped low-rise (< 60 ft.) and medium-rise buildings since the 1970s. Low-rise buildings are fully immersed within the high turbulent portion of the boundary layer wind flow. Therefore the wind loads on the building and roof are quite significant, and will be the focus of this section. This section summarizes the general behavior of roof pressures over a flat roof. **Table 1** reviews and the general methodology for past flat roof wind studies.

Table 1. Flat roof wind flow studies' parameters for low-rise buildings

Cited Reference/ Year	Scale	Exposure	L/B*	H/B*	Wind Angle
(Kramer, et al./1978)	Not provided	Not provided	1.0 2.0 3.0	0.25 0.5 1.0	0° 45°
(Lythe and Surry, 1982)	1:500	Open	2.0	0.2 0.35 0.5 1.0 2.5	0° 45°
(Stathopoulos, et al., 1990)	1:1	Open Suburban	-	-	0° to 90°
(Surry, 1991)	1:100 1:1	Turbulence profile provided	1.5	0.42	0° to 90°
(Bienkiewicz and Sun, 1992)	1:25	Turbulence profile provided	1.5	0.43	0° to 90°
(Baskaran and Savage, 2003)	1:10	Not provided	1.0	0.45	0° 45°

* Dimension ratio with respect to wind angle = 0° (perpendicular to windward edge)

2.1.1 Wind direction

These studies recognized that cornering winds ranging from 30°-45° typically produced negative roof pressure coefficients which were significantly larger when compared to other wind directions. This phenomenon is due to the formation of two conical vortices which create highly turbulent flow across the roof surface. These vortices were visually captured by Bienkiewicz's and Sun's studies in 1992 utilizing flow visualization. Their reasoning behind this behavior was that the conical vortices created a reattachment region separated by the reattachment and secondary separation lines, summarized in **Figure 1** (Bienkiewicz and Sun, 1992). A recent study conducted by Blessing et al. in 2009, looked at mitigation techniques for those conical vortices. The authors spread gravel across a 10 ft x 10 ft flat roof and introduced a cornering wind while varying the edge conditions (parapet types). The authors were able to visually capture the shape of the vortex cones, as shown in **Figure 2** (Blessing, et al., 2009).

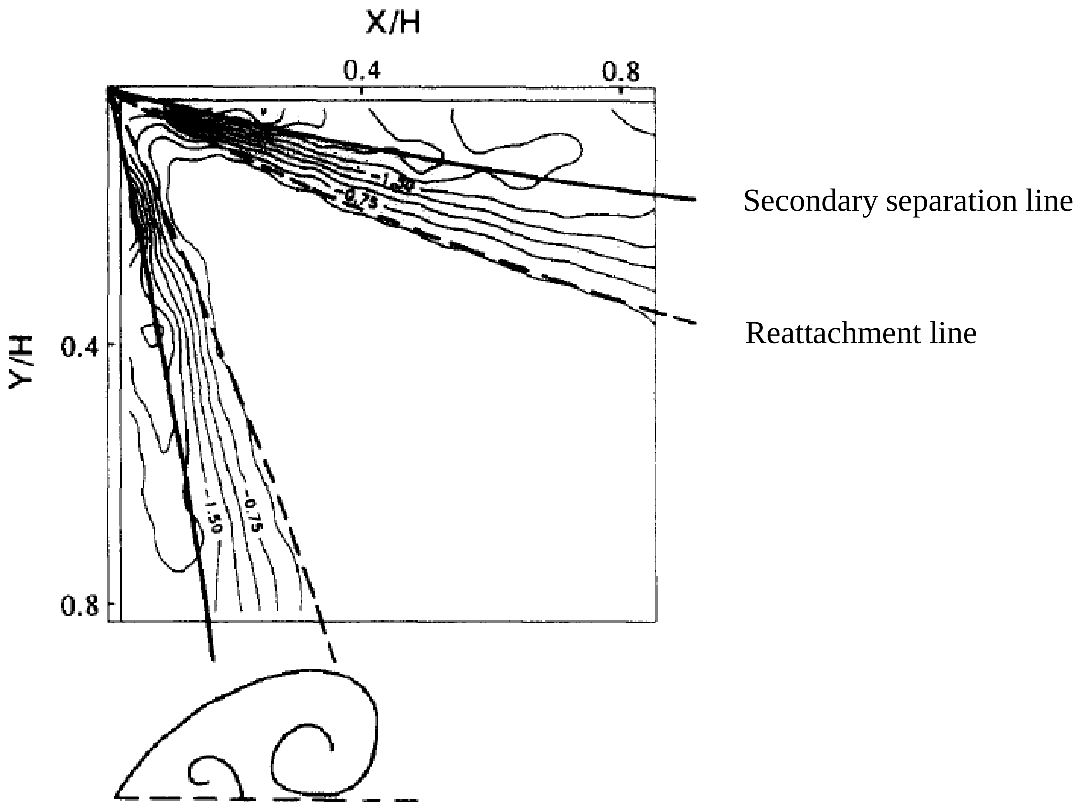


Figure 1. Conical vortex boundaries shown by the secondary separation and reattachment lines (Bienkiewicz and Sun, 1992)

Figure 2. Gravel scour shape with standard edging type (Blessing, et al., 2009)

Bienkiewicz and Sun determined the peak coefficients to range from -9.7 to -11.3 for cornering winds, and about -6.0 for 0° winds (Bienkiewicz and Sun, 1992). Surry measured a cornering wind peak coefficient of -8.4 and a normal wind peak of -3.6 (Surry, 1991). Stathopoulos took field measurements on the corner regions of a full scale roof and found that the highest mean pressure coefficients of -3.5 to -4.5 with cornering winds, while the mean coefficients ranged from -1.0 to -1.3 for normal winds (Stathopoulos, et al., 1990). These values, from several different studies, imply an increase of the magnitude anywhere from 1.6 to 4 times larger when comparing cornering wind pressures to normal wind pressures.

2.1.2 Roof regions and building geometry

The studies reviewed in this section determined the wind pressure distribution across a flat roof due to varying angles of wind flow, as well as varying building geometries. Typically, the building geometric parameters which affect the pressure distribution are the height, H, length, L, and base, B. The base refers to the length of the side perpendicular to the wind flow, and the length refers to the side which is parallel. Therefore, it can be seen that the length and width of a building changes when wind directions change from 0° to 90°.

From the obtained pressure coefficients, it was therefore determined that windward corner and edge regions of the roof experience the highest suction pressures regardless of wind angle. Kramer et al. (1978) found that averaged edge and corner pressure coefficients increased with increasing H/B ratios (Kramer, et al., 1978). Kind (1986) found that unless relatively high parapets are present, worst mean suction coefficients are about -3 to -4 along the edges and corners (Kind, 1986). The field of the roof (interior region) has substantially lower pressure coefficients in comparison, ranging from peak values of -0.4 (Lythe and Surry, 1982) to -1.2 (Surry, 1991). The field pressures will typically decrease with increasing building length.

2.1.3 Parapets as mitigation strategy

A common method of dispersing the high suction pressures present in corner and edge regions of a flat roof through the installation of parapet walls around its perimeter. Parapets force the conical vortices which form at the edges and corners upwards, effectively reducing the suction pressures across the roof (Kopp, et al., 2005). As a result, the vortices are expanded, as evident by the gravel scour patterns in the study completed by Blessing et al. (2009). Extensive research has gone into determining the effects parapets have on the wind loads in the field of bluff body aerodynamics. The general conclusions gathered were:

- Generally, as ratio of parapet height to building height increases, the negative pressure coefficients across the roof decreases (Kind, 1986, Kopp, et al., 2005, Sockel and Taucher, 1981, Baskaran and Stathopoulos, 1988, Stathopoulos and Baskaran, 1988, Kareem and Lu, 1992, Kopp, et al., 2005).
- For low-rise buildings, higher suctions (as compared to roofs without parapets) have been reported when low parapets are installed (Stathopoulos and Baskaran, 1988). It was determined in a later study that for ratios of parapet height to building length (h/L) between 0.01 to 0.02, this phenomenon occurs (Stathopoulos, et al., 1999).
- Aerodynamic modifications to parapet walls (or edge fascia) such as discontinuities, perforations, cuts, or slots may aid in suppressing peak roof suctions better than solid continuous parapet walls (Blessing, et al., 2009, Baskaran and Stathopoulos, 1988, Pindado and Meseguer, 2003, Suaris and Irwin, 2010)

2.1.4 Summary

In summary, these defined roof regions reappear in ASCE 7's wind load provisions, and also in the ANSI/SPRI RP-14 (which extends from ASCE 7). Chapter 30 of ASCE 7 provides the design procedures for components and cladding loads and defines the corner region as zone 3 with GCp = -2.8 to -1.1, edge region as zone 2 with GCp = -1.8 to -1.1, and the field of the roof as zone 1 with GCp = -1.0 to -0.9, as shown in Figure 30.4-2A of ASCE 7-10. By reviewing established literature and the ASCE 7 wind load provisions, a general guideline can be formed for the expected pressure distribution across the built up roof section for the UF studies.

2.2 Ballast pavers on flat roofs

Ballast pavers are cladding roofing elements commonly used as dead load to secure loose-laid roofing membranes. These elements are typically joined edge-to-edge with little or no space between them. Also, spacers separating the bottom surface of a paver to the roof deck may or may not be utilized. This subsection summarizes the findings from previous studies conducted on roof pavers. A comparison between an extensively planted green roof module and a roof paver shows some similitude, but does not provide more than speculation. This subsection's purpose is to better understand the behavior of roof pavers to determine the relationship (if any) between the wind behavior of pavers and green roof modules. **Table 2** distinguishes the chosen parameters between each paver study cited.

Table 2. Paver wind flow studies' parameters for low-rise buildings.

Reference	Scale	Paver Aspect Ratio	L/B	H/B*	Wind Angle
(Kramer, et al., 1979)	1:1	n/a	n/a	n/a	0°
(Kind and Wardlaw, 1982)	1:10	1:1	1.0	0.193	45°
(Kramer and Gerhardt, 1983)	1:1	1:1	1.0	0.194	0° 45°
(Bienkiewicz and Meroney, 1988)	1:15	1:1	1.0	0.682	45°

(Wacker, et al., 1991)	1:250	1:1	1.0	0.670	0° 45°
(Bienkiewicz and Sun, 1992)	1:25	1:1.335	1.496	0.423	45°
(Bienkiewicz and Sun, 1997)	1:25	1:1 1:1.5 1:2	1.496	0.423	45°

*The dimension B refers to the building width perpendicular to the normal wind flow

The wind load on a paver is dependent upon the net pressure, which is the difference of the internal from the external pressure (Cp,net = Cp,ext – Cp,int). The internal pressure for a paver corresponds to the pressure acting on the bottom surface of a paver and is dependent upon the permeability of the paving element. The external pressure on a paver corresponds to the pressure experienced by the top surface, and has a pressure distribution that is very similar to that of a bare flat roof (Kramer, et al., 1979, Kramer and Gerhardt, 1983). Parametric wind tunnel studies shown in **Table 2** varied paver geometry and installation methods on flat roofs, and observed the resulting pressure distributions. These studies found that:

- Failure (displacement of paver) typically occurs as uplift or overturning of the paver when a substantial difference develops between the top surface pressure and pressure underneath (Kind and Wardlaw, 1982)
- The external pressure distribution on the top surface of a paver essentially causes wind flow in the gaps between pavers and void space between the underneath surface and roof surface (Kind and Wardlaw, 1982). The resulting pressure distribution underneath the pavers has been found to be very closely correlated to the external pressure distribution (Kind and Wardlaw, 1982, Bienkiewicz and Sun, 1992) when no gap beneath pavers was present.
- However, an introduction of a void space underneath a paver results in a more uniform underneath pressure distribution (Bienkiewicz and Sun, 1992). Therefore, spacing underneath and between pavers determines the pressure distribution underneath pavers. Paver wind resistance is improved (higher failure wind speed) when the ratio of the space-between and space-underneath pavers is increased (Bienkiewicz and Sun, 1997).
- Failure wind speed of pavers decreases as the turbulence of approaching wind flow increases (Kramer and Gerhardt, 1983, Bienkiewicz and Meroney, 1988).
- Staggered and edge-clipped pavers have higher failure wind speeds (Kind and Wardlaw, 1982, Bienkiewicz and Meroney, 1988, Bienkiewicz and Sun, 1997).

2.3 Embedded gravel on flat roofs

In addition to roof pavers, gravel ballast has been used as dead load to secure loosely-laid roofing membranes atop of roofs. Studies have been conducted which looked at either the critical wind speed where gravel displacement (scour or blow-off) occurred, or the gravel trajectory downstream once blown off the roof. Because green roof systems utilize engineered growth media that aims to minimize the aggregate weight while promoting water retention, green roof growth media may experience blow-off at lower wind speeds if the green roof vegetation is not properly maintained. Therefore, gravel studies which explored the critical wind speeds in comparison to aggregate size provide a methodology of determining the critical wind speeds for green roof systems, as suggested by the ANSI/SPRI RP-14. This section will focus on the mechanics which induce scour or blow-off of individual pieces of aggregate, as specified by previous wind performance studies. Transport and impact of gravel downstream will not be discussed as this will imply failure of green roof systems have already occurred.

2.3.1 Mechanics of failure

A series of wind tunnel studies were conducted by the National Research Council of Canada in the 1970s that exclusively investigated the effects of gravel scour and windborne debris generation on roofs. Kind's first experiment (Kind, 1974) attempted to develop a method of estimating the wind speed at which roof gravel would blow away. He looked at three different gravel types: ¼ to ½ in. pea gravel, ¾ in. natural gravel, and ¾ in. crushed stone. He found that the smaller-sized pea gravel experienced lower critical wind speeds (V_{c1} and V_{c2} defined below) than natural gravel and crushed stone. Kind summarized the moment balance shown in **Figure 3** below. The nomenclature for **Figure 3** is defined as follows:

- D_c = Critical drag force
- k_1, k_2 = Shape proportionality coefficients
- ρ_s = Density of stones
- d = Nominal diameter of stones
- W = Weight of a single stone

His second set of tests varied typical building geometries (plan dimensions, parapet height, and building height) as well as the wind direction and gravel size to further explore how gravel behaves on top of flat roofs (Kind, 1974). Following these tests, Kind identified four different critical wind speeds corresponding to different gravel behaviors:

- V_{c1} – initial large-scale or strong motion of stones
- V_{c2} – scouring occurs more or less indefinitely
- V_{c3} – initial blow-off of the roof by going over upstream parapet (windward parapet)
- V_{c4} – initial blow-off of the roof by going over downstream parapet (leeward parapet)

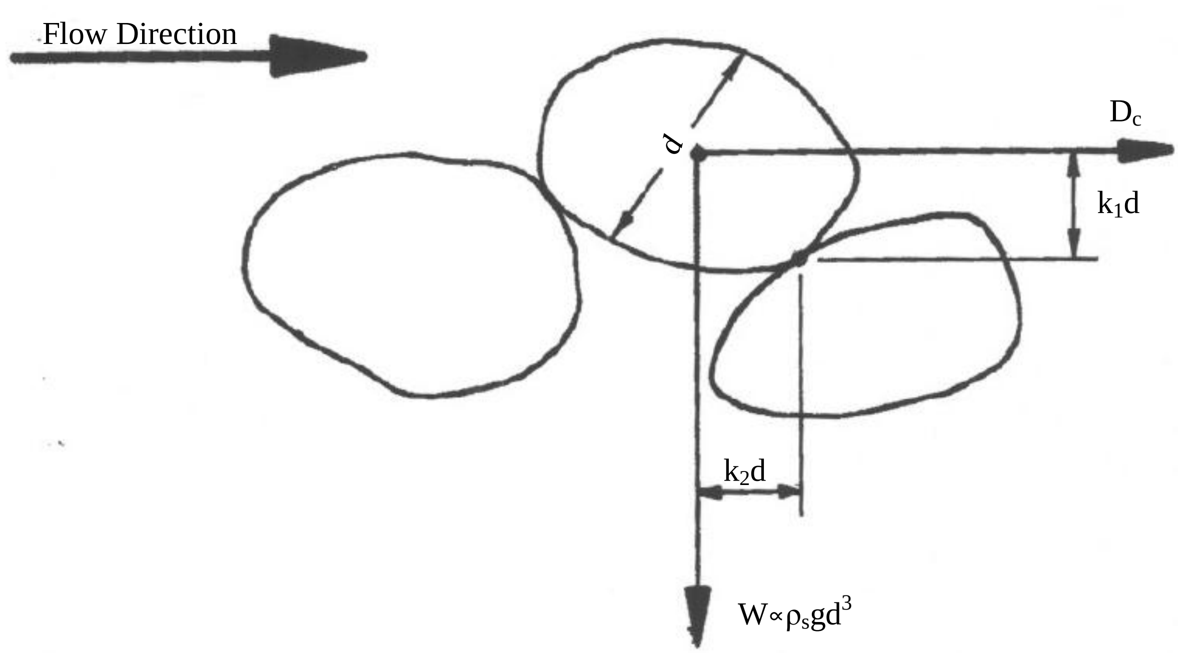


Figure 3. Moment balance on stone at critical condition (Kind, 1974)

2.3.2 Critical wind speed prediction

Kind determined that the first three critical speeds (V_{c1}, V_{c2}, and V_{c3}) were directly proportional to the square root of the aggregate diameter ($\sqrt{d}$) (Kind, 1974), and later found that while V_{c4} did not display the same relationship, the critical speed was normally equal to or greater than V_{c3} (Kind and Wardlaw, 1976). Generally, increasing parapet heights leads to an increase to the critical wind speed, V_{c3}, while increasing the building height decreases it (Kind, 1974).

Kind and Wardlaw (1976) developed a procedure to predict the four critical wind speeds for design. The authors presented figures which predicted results for the V_{c3} and V_{c4} critical speeds with varying parameters (building dimensions, parapet height) (Kind and Wardlaw, 1976) and were tabulated by Masters and Gurley in 2008 for the embedded gravel report submitted to the Florida Building Commission (Masters and Gurley, 2008). The nominal gravel size chosen was 0.63 in. which represented a reasonable “large” gravel size and provided the same mass Masters’s and Gurley’s tabulated data is replicated in **Table 3** below. Masters and Gurley (2008) converted the wind speeds at roof height and open exposure to ASCE 7 equivalent 10 meter, 3-second gusts at suburban exposure by dividing the Kind’s and Wardlaw’s (1976) wind speeds by the corresponding K_z value at each height for Exposure B from ASCE 7’s Components and Cladding chapter. This exposure was selected because it was assumed that graveled roofs would typically exist in commercial districts, but the authors acknowledged that lower threshold speeds (11-13% lower) would occur in open exposure conditions (Masters and Gurley, 2008).

Table 3. Critical 10 m., 3-s gust wind speed thresholds (mph) for 0.63” gravel in urban terrain

	H / h				V_{c3} ASCE 7 Basic Wind Speed Equivalent				V_{c4} ASCE 7 Basic Wind Speed Equivalent			
Parapet Height *H* (ft)	0.5	1.0	2.0	3.0	0.5	1.0	2.0	3.0	0.5	1.0	2.0	3.0
Building Height *h* (ft)												
20	0.025	0.050	0.100	0.150	73	80	94	108	95	98	106	114
30	0.017	0.033	0.067	0.100	71	75	85	94	92	93	95	99
40	0.013	0.025	0.050	0.075	67	70	77	84	87	86	86	88
50	0.010	0.020	0.040	0.060	64	67	72	77	83	82	80	81
60	0.008	0.017	0.033	0.050	62	64	68	73	81	79	77	76

Willis et al. (2002) presented a model to predict the threshold wind speed which initiates flight of a compact object. The threshold wind speed of a compact object was therefore defined as:

$$V = \sqrt{2tg\frac{\rho_m}{\rho_a}\frac{I}{C_F}}$$

where V = wind velocity, t = d = thickness of object = diameter of gravel, g = gravitational constant, I = fixing strength integrity parameter (= 1 for objects resting on the ground), C_F = aerodynamic force coefficient (≈ 1), and ρ_m and ρ_a = densities of object (gravel) and air (Masters and Gurley, 2008, Wills, et al., 2002). Masters and Gurley (2008) found that this model agreed very closely to the results presented by Kind and Wardlaw (1976) by a few mph for a gravel nominal diameter of 0.63 in.

2.3.3 Application to green roof systems

As mentioned in the first paragraph of this section, green roof growth media is typically designed to minimize weight since the depths to which they are applied can vary greatly and have significant impact on the resulting dead load. For typical gravel roof applications, however, the ANSI/SPRI RP-4: Wind Design Standard for Ballasted Single-ply Roofing Systems specifies the usage of #4 ballast (nominally 1.5 in. diameter smooth river bottom stone) spread at a rate of 1000 pounds per 100 square feet in the field area of the roof and #2 ballast (nominally 2.5 in. diameter smooth river bottom stone) spread at a rate of 1300 pounds per 100 square feet in the edge and corner regions of the roof ((ANSI) and (SPRI), 2008). From the experiences of the authors of this report, green roof growth media contains a wide variety of coarse and fine aggregate to allow for minimal weight, while still providing the organic compounds required for plants to thrive. Even so, the coarse aggregate sizing from the two manufacturer-supplied substrates compared to be smaller than the required ballast sizes specified by the RP-4. Therefore, based on the nominal diameter of the coarse aggregate used in green roof growth media, its smaller size would correspond to lower threshold speeds (Kind, 1974, Kind, 1974, Kind and Wardlaw, 1976, Wills, et al., 2002).

Given the presented literature, it should be noted that green roof systems should not be expected to behave like graveled roofs. While bare gravel roofs depend on increased sizing of the aggregate to resist scour and uplift, plants act as the main form of erosion and scour resistance on green roofs (as will be discussed in Section 2.4). For that reason, proper maintenance of green roof plants is required to ensure minimal growth media losses when exposed to high winds.

2.4 Wind studies on plants at ground level

Although the study of bluff body wind flow effects on green roofs has mostly been unexplored, the wind effects on various types of vegetation commonly found at ground level has been well documented. Vegetation has been commonly used as a natural method to prevent scour and erosion of soil. For instance, the vegetation seen on sand dunes in coastal areas act as the dunes' main protection against erosion due to the high winds. Since many of these studies aimed to create realistic wind velocity profiles, it could be theorized that the same experiments presented in this section could be represented by green roof systems tested at various heights above ground level to represent different building heights. However, because live vegetation cannot be scaled down for wind tunnel model studies (with similar difficulty to create scale models which carry the same plant characteristics), exploring these effects would prove highly infeasible. This section will present the mechanics behind plant scour resistance, and then the common failure modes experienced in plants.

2.4.1 Plants' role in soil transport and shear stress resistance

Vegetation protects a soil surface from wind erosion through direct cover and sheltering of the soil surface, trapping of airborne soil particles, adding cohesiveness to the soil via root moisture and also by extracting momentum from the air flow through the stalks and leaves, effectively reducing the surface wind stress (Lancaster and Baas, 1998, Kim, et al., 2000). A summary of the soil transport mechanics is shown below in **Figure 4**. The threshold velocity of sand particles was explored by Lancaster and Baas (1998) via field studies of vegetation at Owens Lake, California. This resulted in wind tunnel studies which explored similar issues by Kim et al. (2000) and Burri et al. (2011) with grass plants. The authors found that larger plant sizes increased the threshold shear wind velocity (Lancaster and Baas, 1998). The three studies also found that increasing vegetation cover exponentially decreased the sediment flux (Lancaster and Baas, 1998, Kim, et al., 2000, Burri, et al., 2011). Both wind tunnel studies by Kim et al. (2000) and Burri et al. (2011) attributed the lower instances of sediment displacement to not only increasing coverage ratios, but also to the increased coverage ratios promotion of momentum reduction via direct particle impact with plants (Kim, et al., 2000, Burri, et al., 2011).

A 2011 study by Walter et al. took a new approach to provide a method of spatially resolving the shear stress distributions underneath live plant canopies. The authors fixed pressure probes in an array around a single plant and varied three plant canopy densities, as well as an unplanted case. The instrumented plant was surrounded by a staggered array of plants to mimic field conditions. The investigators then ran the simulator at three different wind speeds for the three densities and obtained the surface shear stress distributions, normalized by the unplanted case for any possible instrumentation errors. The results confirmed with previous studies that higher momentum absorption and increased sheltering effect can be seen with increasing canopy densities (Lancaster and Baas, 1998, Kim, et al., 2000, Burri, et al., 2011, Walter, et al., 2011). Reduced momentum absorption in lower canopy densities was linked to streamlining effects due to decreased plant frontal area. The spatial surface stress distributions also related the streamlining effect to slightly increased values at the sides of the plant (Walter, et al., 2011).

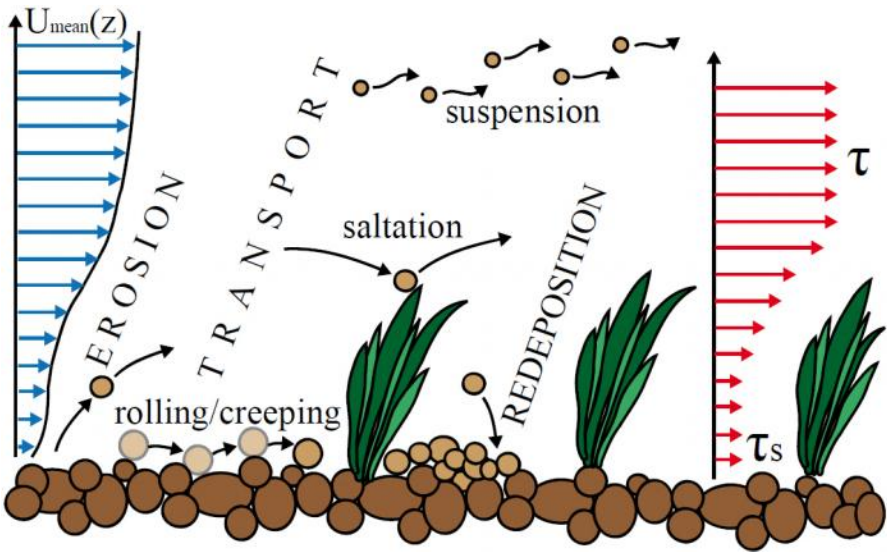


Figure 4. Turbulent boundary layer and aeolian processes over a vegetated surface. U_{mean} is the mean velocity, τ is the total shear stress and τ_s is the reduced shear stress acting on the ground (Walter, et al., 2011)

Dong et al. (2001) aimed to define the relationship between roughness length, drag coefficient and the structural parameters of standing vegetation through wind tunnel studies with modeled cylindrical wooden dowels staggered in an array, and determine which of these factors have the most pronounced effect for wind erosion protection. However, due to plant flexibility, their role as roughness elements is highly dependent upon wind speed as suggested by Kim et al. (2000). This was a limiting factor that Kim et al. acknowledged for wind tunnel studies which fabricated plant models for test specimens. Dong et al. (2001) determined that the height-to-spacing ratio (effective lateral cover) is the best parameter to consider for standing vegetation protection effects on wind erosion (Dong, et al., 2001).

2.4.2 Plant structure failure mechanisms due to wind loads

The previous subsection explored the resistance methods plants have to the shear wind forces which account for scour of surface growth media. This subsection, however, will discuss previous findings on plant failure mechanisms due to excessive wind loads. The main wind-induced plant structure failure mechanisms are stem breakage or plant uplift/uprooting. Because plant failure can cause significant reductions for a crop harvest yield, plant failure studies has appropriately been heavily focused on agricultural plant species. It must therefore be distinguished that green roof plant species and common crop species will likely differ in stem and root structure properties in that many of the plants used in green roofs are low groundcover types and sometimes succulents as opposed to agricultural crops. However, within both types of plant species, when exposed to extreme conditions, have the possibility of failure at the stem or root.

2.4.2.1 Stem failure

Stem breakage is more commonly known as stem lodging, and is the permanent displacement of stems from the vertical (Sterling, et al., 2003, Duan, et al., 2006, Jin, et al., 2010). Stem lodging typically occurs after the base-bending moment of a single shoot exceeds the failure moment of the stem base (Berry, et al., 2006). Jin et al. (2010) looked at two cultivars of rice plants and confirmed that higher bending strengths (via three-point bending test) of the rice stems would result in higher lodging resistance (Jin, et al., 2010). They also found that the type of fertilizer used during plant growth could either aid or damage the plant's stem lodging resistance. They determined that over-applied nitrogen fertilization increased the risk of lodging (as also found by (Sterling, et al., 2003)), while the combined use of potassic and silicon-containing fertilizers could effectively increase basal stem diameter, wall thickness and weight, which effectively increases stem lodging resistance (Jin, et al., 2010). This finding is consistent with Berry et al.'s 2006 lodging study of barley plants, where the main parameters considered to calculate stem lodging were the material strength and thickness of the stem wall, as well as the stem diameter (Berry, et al., 2006).

Sterling et al. (2003) performed field studies on wheat crops subjected to different wind flow conditions. The authors found that stem lodging occurs more or less instantaneously, under a discrete load (wind gust). The discrete load's effectiveness in causing both root and stem lodging is dependent upon the phase of crop motion, i.e. the peak bending moment occurs when this load is imposed on a crop bent along the wind direction (Sterling, et al., 2003). The upshot of this study led to a model which predicted failure wind speeds for wheat lodging (Berry, et al., 2003). The authors identified that the natural frequency, damping ratio, drag coefficient, and center of gravity height of the wheat shoot must be accurately depicted or prediction errors of up to 50% could occur (Sterling, et al., 2003).

2.4.2.2 Root failure

Root failure mechanisms can be distinguished between root lodging and root uplift. Root lodging is similar to stem lodging, in that the plant is permanently displaced from the vertical, but due to failure of the soil instead of the stem (Sposaro, et al., 2008). Root lodging, therefore is a result of the wind-induced and self-weight loads, causing stresses within the plant to cause collapse at the base. This differs from pure uprooting forces, which would typically occur due to an applied vertical force, i.e. grazing herbivores (Ennos, 1989). Simply, root lodging involves transverse loading on a plant while root uplift is the pure vertical loading. While different, these failure modes are closely related, and will be discussed briefly in this subsection.

2.4.2.2.1 Root lodging

Root lodging has been found to be highly dependent upon soil conditions. Sterling et al. (2003) found that root lodging of the wheat crops only found to occur when the soil strength was reduced by extensive wetting. However, plants' properties are consequently dependent upon the condition of the soil they are grown in. Studies have suggested that the plant responses to weak soil conditions often are compensated in its root growth. Goodman and Ennos (1999) found that sunflower root spread exhibited much wider angles in strong soils than weak soils. This resulted in wider root plate diameters, and therefore less root lodging occurrence. Their results suggested that the plant compensation for weak soil conditions does not adequately resist lodging effects alone (Goodman and Ennos, 1999).

Plant conditions which effect root lodging are root growth, shape, strength, and density, and mechanical properties of the plant sections exposed to wind. Sposaro et al. (2008) found that decreased crop population densities allowed for larger root plate diameters. Furthermore, they found that sunflower plants with greater root plate diameters exhibited greater root failure moments (higher resistance to root lodging). Sterling et al. (2003) captured video recording of the lodging of wheat and found that root lodging typically occurs progressively over a period of a few minutes due to a series of discrete loads (rather than instantaneous stem lodging as mentioned above). Their results suggest that plant and/or soil fatigue effects exist in root lodging, and cannot be assumed to occur instantaneously when the plant base bending moment exceeds the strength of the root soil combination (Sterling, et al., 2003).

2.4.2.2.2 Root uplift

The other type of root failure studied in literature has been pure, vertical uplift of a plant and root system. Anchorage of a plant plays an important role in uplift resistance, and studies therefore focused much of their attention to the root structure of the uplifted plant:

- Ennos (1989) closely observed the uprooting effects in sunflower root systems and found that the upper portion of the roots fully mobilize its shear strength to resist uplift while the lower portion contribute little resistance due to debonding between soil and root (Ennos, 1989).
- Bailey et al. (2002) found in their uplift tests that as a plant is uprooted, sudden drops in the tensile force versus displacement trace were due to individual root breakage. The investigators stated that individual root strengths were additive, and summed up to the peak pulling resistance of the plant – an additive property deemed as root co-operation. Root co-operation and the lateral root systems were determined to greatly contribute to plant anchorage while root hairs have little effect (Bailey, et al., 2002).
- Mickovski et al. (2005) performed uplift tests on vetiver grass specimens and determined statistically significant positive correlations between the maximum uprooting force and plant height, as well as the uprooting force and lateral root spread. The authors found the maximum uprooting force ranged from 190 to 620 N (43 to 140 lb). Taller plants were said to be healthier, and therefore have more abundant and stronger root systems than shorter plants, strengthening their resistance to uprooting. While the vetiver specimens typically had very little lateral root spread, the authors found that those which spread wider resisted uprooting better than specimens which had purely vertical root systems (Mickovski, et al., 2005).
- Hamza et al. (2007) combined mechanical uplift tests with digital analysis to determine the root displacement behavior for branched and unbranched root systems. The uproot tests showed that the specimens with two lateral root branches had the highest uplift force required for failure (2.5 N as compared to ≈1.5 N) (Hamza, et al., 2007).
- Mickovski et al. (2010) attempted to simplify the complexity of plant root systems and perform uplift tests on fabricated cylindrical unbranched root models made of rubber and wood. Longer rubber root lengths resulted in higher pullout forces (3.5 N for 120 mm root) and reaffirmed the same conclusion by Mickovski et al. (2005). That same length of rubber root also resulted in the highest shear stress between the root and soil. Model roots still underestimated the pullout force required when compared to real Willow roots, and

possibly attributed to different roughness conditions and non-linear shape (Mickovski, et al., 2010).

2.4.3 Summary

Section 2.4 presented existing vegetation research on its role in shear stress and soil transport resistance, as well as its common failure mechanisms. There is qualitative relationship between roof gravel (Section 2.3) and ground-level plant wind studies, as both provide potential for windborne debris. Plants, however, have been shown to reduce such debris generation at ground level, through their role in soil stabilization and momentum reduction. However, the question still looms as to how they will perform when introduced to bluff body effects from low- to high-rise buildings (one of the objectives of this research study). This section reviewed three different failure modes that plants may experience: stem lodging, root lodging, and root uplift. Stem and root lodging will most likely dominate the failure methods that green roof vegetation will experience when wind loads are induced. Root uplift of green roof plants due to a vertical force as a failure method may not be realistic, and may blend with root lodging to form a combination failure mode. These lingering unknowns are due to the largely unstudied subject field, and are part of the motivation behind this report.

THIS PAGE IS LEFT BLANK INTENTIONALLY

3 GREEN ROOF WIND PERFORMANCE STUDIES

Section 3 provides a review of the two green roof wind performance studies and a case study of a green roof system which withstood multiple high-wind events.

3.1 Southern Illinois University Edwardsville (SIUE)

In 2009, researchers at SIUE, along with consultants from the National Roofing Contractors Association (NRCA) and Green Roof Blocks conducted a wind tunnel study on green roof modules. These specimens were initially tested as 24 in. x 24 in. x 4 in. deep, aluminum modules, and later fabricated to fit into 18 in. x 18 in. x 4 in. deep, aluminum modules. The authors also tested fabric green roof modules measuring 20 in. x 32 in. x 5 in. deep

A recirculating wind tunnel was used to generate the wind flow on individual green roof modules. It used a two-stage axial fan driven by a 300 HP electric motor, and was able of producing wind speeds of up to 140 mph. The test section measured 72 in. long, 30 in. wide and 24 in. high. The authors recorded a peak turbulence intensity of 0.22% at its highest velocity.

The authors conducted a total of 21 test trials of a two different testing dates (Test Day 1 – June 13, 2009 and Test Day 2 – August 9, 2009). Green roof specimens were tethered (with sufficient slack to allow module displacement failure) to prevent module-induced damage to the test chamber during testing, and a layer of EPDM was applied where the specimens where placed to simulate real roof conditions. The specimens were placed at 45° to wind direction to simulate local cornering wind effects. Wind speeds and duration for each test trial was planned as: 60 mph (1 min), 75 mph (1 min), 90 mph (2 min), 105 mph (3 min), 120 mph (5 min), and 140 mph (5 min). Failure was defined as one of the following conditions:

- Displacement of green roof module
- Displacement of vegetation (more than shedding of a few leaves)
- Displacement of growth media (more than minimal scouring)

The authors identified three main hypotheses:

1. Four inches of fully vegetated growth media can sustain two minute wind gusts greater than 90 mph
2. There is a minimum level of vegetation required to bind the growth media in order to resist scour during two minute wind gusts greater than 90 mph. Identify that level.
3. There are surface treatments that are effective in minimizing scour at various wind speeds. Identify the treatment and the wind speed at which it is no longer effective.

Hypothesis #1 was tested with fully vegetated modules (no bare media exposed) at the assigned wind speeds and noting the outcomes. Hypothesis #2 required modules of varying levels of vegetative coverage (calculated prior to each test trial) to be pre-grown at a local nursery. Hypothesis #3 was tested with nonvegetated modules treated with either liquid binding agents or erosion control blankets.

From the test trials, the authors found:

- Hypothesis #1 was confirmed:
  - A fully vegetated 24 in. x 24 in. x 4 in. module facing 90° winds could withstand 120 mph wind speeds for 5 min., but experience full module displacement when attempting 140 mph. The same module setup could withstand 140 mph wind speeds for 5 minutes without modular displacement if air flow was prevented from passing underneath the module.
  - Fully vegetated 18 in. x 18 in. x 4 in. modules with cornering winds could withstand both 140 mph winds for 5 minutes and modular displacement without growth media or vegetation loss.
- Hypothesis #2 was confirmed:
  - Nonvegetated modules with dry growth media are sensitive to relatively low wind speeds, experiencing scour at speeds as low as 30 mph.
  - Partially vegetated modules experienced growth media scour after 75 mph and could not reach the target of 90 mph. Therefore, the minimum level of vegetation was determined as 100% coverage.
- Hypothesis #3 was confirmed:
  - No wind scour was observed for Liquid Binding Agent A at 140 mph, the 100% natural burlap blanket at 120 mph, and Liquid Binding Agent T at 90 mph.

The results from this study were utilized in forming the ANSI/SPRI RP-14. The authors acknowledge that this study is simply the beginning of further testing of individual components and total systems required in the near future (Retzlaff, et al., 2010).

3.2 University of Central Florida (UCF)

Wanielista et al. (2011) conducted field monitoring studies funded by the Florida Department of Environmental Protection (FDEP) on the natural wind effects on two existing green roofs in Florida. The authors also present preliminary results from a wind performance study performed with Florida International University's (FIU) Wall of Wind. The authors were outlined their objectives based off of three questions:

1. Do winds have an effect on green roof material loss?
2. Do green roof materials modify local pressure conditions that would need a modification to current design codes?
3. Does the level of vegetation establishment affect the material loss and pressure distribution?

3.2.1 Full-scale wind experiment

To attempt to answer these questions, Wanielista et al. (2011) planned for full-scale wind performance experiments on built-in-place green roof systems utilizing FIU's Wall of Wind (WOW) – a wind simulator made up of six propeller drives, each powered by its own big block carburetor engine. Utilizing the existing 10 ft. x 10 ft. x 10 ft. structure from Blessing et al.'s study (2009), a green roof system was to be installed on its roof and exposed to cornering winds (which has been shown to create the highest roof suctions). The authors designed a test matrix that explored the effects of varying parapet wall heights (0 ft., 1 ft., and 3 ft.), the usage of erosion control (bare green roof, wind netting, or polymer), and the establishment of the green roof vegetation (new or established) for a total of 18 test trials.

The green roof system incorporated an edge restraint around the perimeter of the building. With the bottom roof deck layer, the following components were installed: a thermoplastic protection layer, drainage layer with integrated separation fabric, 1 in. of pollution control media, separation fabric, and 3 in. of growth media. To explore the worst case scenario, the authors did not mechanically attach or adhere the system to the roof deck (utilizing the dead weight of the growth media as ballast), and utilized bare growth media without any saturation or erosion control for the initial test trial.

The system was first exposed to 30 seconds of 58.9 mph. Upon ramping up to 77.8 mph, the authors noted that the edge restraint suffered failure at 35 seconds of total testing (after time zero). The wind generator operated until 60 seconds had elapsed with the 77.8 mph wind speed. The authors attributed the edge restraint and resulting growth media system failure to uplift forces formed by the wind interaction with the corner of the building. Soil cracking was also observed close to the edges of the roof.

3.2.2 Field monitoring study

For the monitoring study, the authors look at two green roofs located on the East and West coast of Florida. The East coast well-established vegetated roof was planted in the summer of 2007 as part of the Florida Showcase Green Envirohome (FSGE) in Indiatlantic, FL. The West coast newly-established vegetated roof was constructed in the beginning of 2009 atop of the club house of the Port Charlotte Rays Stadium (PCRS) in Port Charlotte, FL. These green roofs were chosen for the monitoring study due to being on opposite coasts and close to the shoreline where the highest wind loads were predicted to occur.

The FSGE green roof was built on an 8 ft. tall structure and measures about 50 sq. ft. with no parapet. The PCRS green roof, however, was installed as a rectangular section on top of a flat roof at 25 ft. high, with an area of 1600 sq. ft. and a parapet height of 31 in. The green roof strip did not extend to the full area of the roof, but rather, its short side and long side sat 6.4 ft. and 16.9 ft., respectively, away from the parapet perimeter. The authors decided to only instrument the ends of the PCRS green roof due to the vast area difference between the two systems.

Both systems were instrumented utilized a four blade wind anemometer to determine the wind speed and direction and a series of bi-directional pressure transducers (12 on FSGE, 24 on PCRS) to obtain the pressure distribution across the surface of each green roof. Data collection of both sites was taken simultaneously from June 2009 to February 2010 to attempt to capture the most active wind events during the 2009's hurricane season.

The authors found that the FSGE green roof recorded a maximum wind speed of 22 mph, and displayed a fairly uniform trend from on pressure tap to another. This was linked to the building's simple shape and small size. The PCRS green roof also recorded a maximum wind speed of about 20 mph, but displayed highly random pressure results between taps. The authors attributed this behavior due to a large wall obstruction located on the southwest end of the club house, as well as the PCRS's parapet wall.

3.2.3 ASCE 7-05 pressure calculation and comparison

The authors used ASCE 7-05's components and claddings analytical method to calculate the pressures across each roof and compare with the field pressure predictions. ASCE 7-05 components and claddings loads were obtained for both green roofs with a design wind speed of 130 mph in an exposure C category. Zone 1, 2 and 3 pressures were calculated for both the FSGE and PCRS green roofs, and represented the ASCE 7 minimum design pressures.

The investigators identified the lack of control over obtaining sustained wind speeds and wind direction as key limitations in comparing their field data with ASCE 7 loads, since the components and claddings loads only account for wind speed as the main factor in determining the pressure distribution. The external pressure coefficients on each tap consequently changed with the direction of the wind. To compensate, the authors calculated the average worst case minimum, maximum and mean pressure coefficients for each pressure tap, with respect to wind direction and wind speed. The authors then plotted the minimum and maximum pressure coefficients with respect to wind direction and determined which wind direction gave them the highest uplift pressure coefficients. The minimum pressure coefficients were then averaged within the cluster of pressure taps which corresponded to the defined ASCE 7 roof zones (only Zone 1 for the PCRS green roof). This averaged minimum pressure coefficient was then used with an assumed design wind speed of 130 mph to calculate the predicted roof pressures for each green roof. These pressures were then compared to the corresponding ASCE 7 loads calculated earlier. The comparison showed that while the Zone 2 pressures generally agreed for the FSGE green roof (measured -49.30 psf vs. calculated -43.27 psf), the ASCE 7 loads either grossly overcompensated or under predicted the pressures the roof actually experienced (twice as high calculated FSGE Zone 3 pressure, and half as what was calculated for the PCRS Zone 1 pressure) (Wanielista, et al., 2011).

3.3 Bonita Bay green roof

The series of hurricanes which struck Florida (and elsewhere) in 2004 exposed many of the weaknesses in its building stock. Because these four systems (Charley, Frances, Jeanne and Ivan) struck Florida back-to-back, many of these building weaknesses were further impacted and damaged by subsequent storms. The Federal Emergency Management Agency (FEMA) reported that damage from these storms required over $4.4 billion in disaster resistance for over 1.24 million victims in Florida by 2005 (FEMA, 2005). This subsection looks at the reported performance of the Bonita Bay green roof located on Florida's gulf (west) coast. Therefore, the focus will revolve upon comparing the roof damage reports due to Hurricane Charley with the observations made on the Bonita Bay green roof.

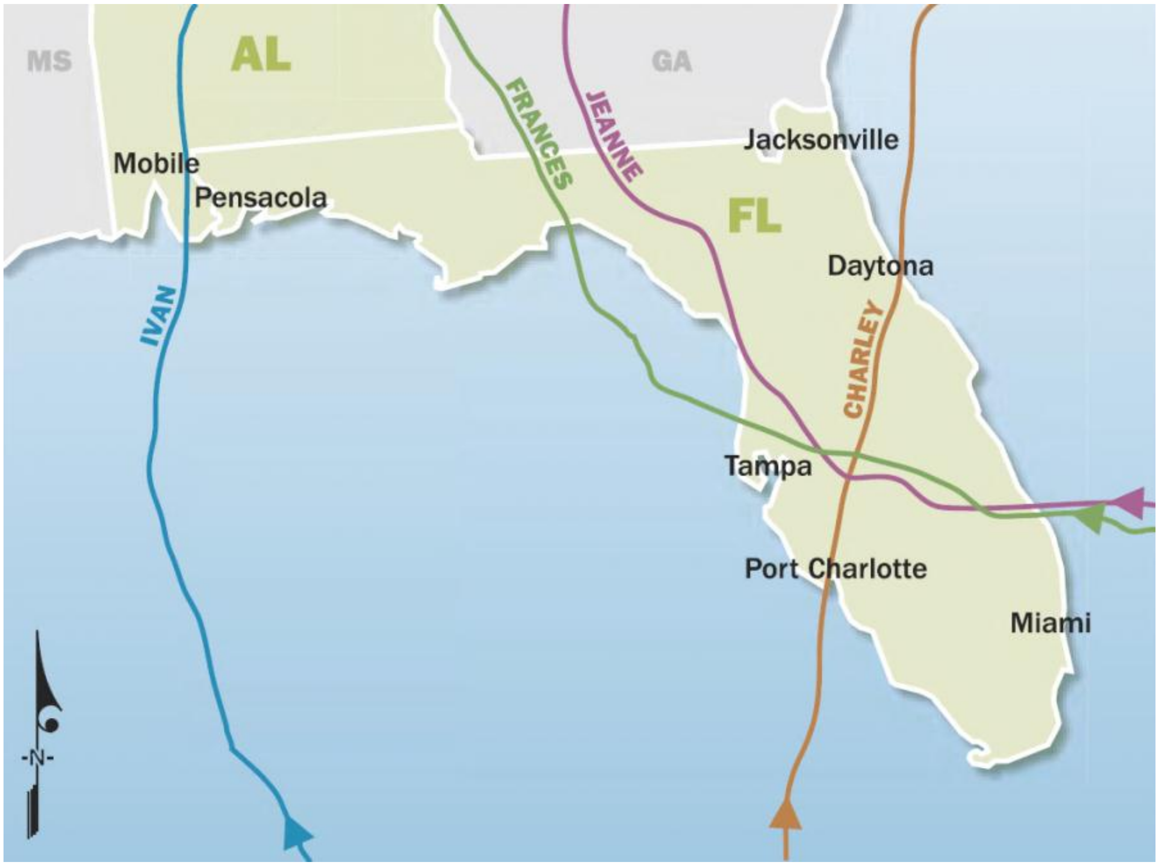


Figure 5. 2004 hurricane paths across Florida ((FEMA), 2005)

On August 13, 2004, Hurricane Charley made landfall at Port Charlotte and the community of Punta Gorda on the gulf coast of Florida as a Category 4 hurricane. **Figure 5** above shows the Charley's path across Florida. At landfall, wind speeds estimated over 150 mph sustained winds and 170 mph gusts. Significant roofing failure was reported for residential systems such as asphalt shingle, clay tile roofs and even metal roofing. FEMA (2005) also found multiple instances of flat roof damage due to Charley. The assessment reported gravel ballast, gutters and even walkway pads being blown off of a hospital in Arcadia (approximately 30 miles inland from Port Charlotte) forming wind-borne debris. In Port Charlotte, FEMA reported aggregate blow-off from a hospital, as well as roof edging failure (similar failure was observed in Cape Coral) ((FEMA), 2005).

Figure 6. Bonita Bay green roof (outlined in red) (Source: Bing Maps)

A site assessment was conducted on the Bonita Bay green roof located in Lee County following Hurricane Charley (2004). The green roof was constructed 15 ft. atop a metal roof of a storage facility at the Shadow Wood Preserve Country Club (shown in **Figure 6**), approximately 50 miles southeast of Port Charlotte. The green roof utilizes a high-strength reinforcing mesh that extends 6.5 ft. inwards from the edge of the roof, attached to the aluminum edging which surrounds the roof. Also, the green roof was installed with one-food wide concrete pavers around the roof perimeter (Miller, 2007). A visual analysis of photos taken before (July 28, 2004) and after (August 19, 2004) Hurricane Charley showed little evidence of plant loss or growth media erosion (Wanielista, et al., 2011). Miller (2007) also reported that the green roof performed very well following Tropical Storm Frances (retired rating once reaching Tampa in 2004) with 60 mph winds, as well as Hurricane Wilma (2005), a Category 3 hurricane with 111 mph to 130 mph winds which hit the gulf coast similar to Hurricane Charley (Miller, 2007).

3.4 Summary

The review presented in this section provides a good baseline of how to shape future research work in addressing wind performance issues with green roof systems.

The work completed at SIUE produced results which reinforced the existing research results summarized in Section 2.4. However, the investigators of this report noted that several limitations from the SIUE study may need to be addressed in future work:

- The wind tunnel cross section measured 24 in. x 30 in. (720 sq. in.), while the cross section of a single module (excluding plants) varied from 4 in. x 18 in. (72 sq. in./10% of wind tunnel cross sectional area), 4 in. x 24 in. (96 sq. in./13%), and up to 5 in. x 20 in. (100 sq. in./14%) (Retzlaff, et al., 2010). This percentage (or ratio) of the specimen cross sectional area to the wind tunnel cross sectional area is also known as the blockage ratio. Blockage ratio contributes to significant increases around the model if large enough, and may not be representative of field conditions. It has been advised to minimize this value to less than 5% to avoid any errors (Holmes, 2007). However, because this study was exploring the direct effect of wind on a green roof specimen, the importance of this may not be significance.
- The turbulence intensity of the wind tunnel was less than 0.25% (Retzlaff, et al., 2010). As shown in Section 2.2, as the turbulence intensity of an incoming wind flow increases, the speed needed for paver failure (displacement) was shown to decrease. While the relationship between pavers and green roof modules has not explicitly been explored, the same phenomenon may or may not be experienced and needs to be addressed.
- The SIUE study considered only a single green roof module specimen per test trial (Retzlaff, et al., 2010). This would be representative of the worst case scenario, but the interrelationship of modules set in an array would be representative of typical installation scenarios. The absence of a built up structure may eliminate any significant uplift forces present in the SIUE study, which has been shown (Section 2) to cause significant roof loads that can affect the performance of common roofing materials and components.

The wind study completed by Wanielista et al. (2011) presented valuable methodology considerations for future research on the topic of green roof wind performance.

- The test matrix presented for the wind generator study was very similar to the approach taken by the investigators of this report.
- While the conclusion that uplift occurred at the leading corner of the green roof to cause initial failure of the roof edging, the fact that none of the components were mechanically attached may have perpetuated the failure. Once wind flow was introduced underneath the edging and subsequent green roof layers, the uplift force due to wind acting on the underside of the layers and an overturning moment introduced to the edging by the laterally moving wind may have combined to create the failure. Studies at the University of Florida have attempted to control such roof structure failures by isolating the green roof systems for testing.
- The pressure data presented by the study, while problematic in comparing with calculated ASCE 7 wind loads, was the first attempt (to these investigators' knowledge) at obtaining full scale green roof pressures. One main limitation was the absence of high force wind events during the data acquisition period – one that was out of the authors' control. Other limitations that may have adversely affected the obtained results were the small size of the FSGE green roof and the small number of taps utilized for such large models.

Finally, the case study of the Bonita Bay green roof's resistance against high wind events while reported roof failures around the same region occur provides at least one success case of green roof systems thriving in Florida.

4. EXISTING GREEN ROOF DESIGN GUIDELINES

Several green roof design specifications are readily available to manufacturers and designers seeking guidance in installation. For the purpose of this study, design guidelines were narrowed down to either strictly designing for wind hazards, or addressing a method/means to safely account for those wind loads. The only guidelines available (to these investigators' knowledge) which fit into these two categories are the Forschungsgesellschaft Landschaftsentwicklung Landschaftsbau e.V. (FLL) Standard: Guidelines for the Planning, Construction and Maintenance of Green Roofing, Factory Mutual (FM) Global 1-35: Property Loss Prevention Data Sheets for Green Roof Systems, and ANSI/SPRI RP-14: Wind Design Standard for Vegetative Roofing Systems. **Table 4** summarizes these standards/guidelines. Section 4 will present the methodology/approach which these three green roof design guidelines place on addressing the potential wind hazards as well as considerations taken in the plant design and selection.

Table 4. Summary of green roof design guidelines/standards

	FLL[1]	**FM 1-35**[2]	**RP-14**[3]
Latest edition	2008	2011	2010
Guideline type	Comprehensive design	Comprehensive design	Wind design standard
Plant selection guide	Yes	No	No
Wind design reference	DIN 1055-4	FM 1-28 FM 1-29 FLL	RP-4 ASCE 7-05 FLL DIN 1055-4 Various studies
Wind speed restriction	None – determine loads	< 100 mph (3-sec gust) – hard restriction	< 140 mph (3-sec gust) – defaults to engineer
Building height restriction	None – determine loads	150 ft. – dictates ballast requirements	< 150 ft. – defaults to engineer
Deck material restriction	All; Roofs with coverings require further permit	Only use metal or structural concrete	All; Determine impervious or pervious deck
Parapet wall requirement	No	Yes	Yes
Roof slope	1.1 - 45°	1.1 - 40°	1.1 - 7°

	FLL[1]	FM 1-35[2]	RP-14[3]
Erosion control methods	-Stable substrates -Soil fixer -Hard stone chippings -Fast-growing, high-coverage plant species -Wet seed -Pre-cultivated vegetation matting -Erosion protection mat	-Erosion protection mat	-Soil tackifier -Erosion protection mat
Wind design method	1. Calculate wind loads from DIN 1055-4 2. Determine critical roof regions for building 3. Design green roof system's vegetation and growth media	1. Supporting roof structure designed based off FM 1-28 2. Conditional steps used to determine whether green roof growth media can be used as ballast against wind uplift or secondary ballast.	1. Determine building and geographical parameters (building & parapet heights, wind speed, exposure, etc.) 2. Based on step 1, utilize design tables to determine green roof system design (1, 2, or 3) 3. Determine ballasting requirements 4. Make enhancements if necessary

[1] ((FLL), 2008)
[2] (Global), 2011)
[3] ((ANSI) and (SPRI), 2010)

4.1 FLL Standard

The FLL Roof Greening Guideline has existed in various forms ever since 1982, and has been the predominant green roof design guideline for Germany, and the benchmark for several neighboring countries' own regulations. The FLL Standard has also been used in design by various U.S. green roof manufacturers, and has served as a baseline standard for many of the U.S. green roof guidelines. The standard is valid for intensive, simple intensive (commonly termed as semi-intensive elsewhere), and extensive green roof systems, and is closely linked to many of the European DIN Standards. While the FLL Standard is a comprehensive guideline for green roof design, this report will summarize the considerations made for the proposed green roof site conditions, addressing wind hazards, and appropriate plant selection.

4.1.1 Site conditions

Prior to installation, the FLL Standard's crucial, initial step to formulating the optimal green roof design is in identifying site conditions for vegetation. Site conditions are based on three different parameters listed below ((FLL), 2008), with underlined items representing important factors which must be addressed for green roof installations in Florida:

1. Climate and weather-dependent factors
    - <u>Regional climate</u>
    - Local microclimate
    - <u>Pattern and volume of annual precipitation</u>
    - <u>Average exposure to sunshine</u>
    - <u>Any periods of drought</u>
    - Any periods of frost, with or without snow cover
    - <u>Prevailing wind direction</u>
2. Structure-dependent factors
    - <u>Sunny, shaded and half shade areas</u>
    - Deflection of precipitation by structure
    - Effect of flue gas emissions (e.g. from fossil-fuel combustion)
    - <u>Wind flow conditions</u>
    - Exposure of the roof surfaces
    - Stress due to reflecting facades
    - Additional water load from adjoining structural elements
    - Gradient or pitch of the roof surfaces and lengths
    - <u>Design loads and the resulting depth of the layered structure</u>
    - Additional technical installations (e.g. air-conditioning units, antenna, solar panels)
    - Roof ponding effects
3. Plant-specific factors
    - <u>Hardiness (robustness) of selected plant species</u>
    - <u>Wind stability in exposed positions (especially for shrubs and perennials)</u>
    - Sensitivity to reflected light and thermal build-up
    - Sensitivity to airborne chemical and exhaust contaminations, as well as warm and cold air emissions
    - Plant runners (stems which run horizontally within the ground rather than vertically)
    - Aggressiveness of rhizome-growth (rhizome is the portion of the plant stem under the ground surface where root-growth stems)
    - Growth pressure of plant rhizome and roots on building elements
    - Competitiveness of plant species in shallow substrate thicknesses
    - <u>Effect of wind and intensity of solar radiation on water storage</u>
    - Demands of aeration in the substrate made by plants in dry locations

4.1.2 Wind design

The FLL Standard recognizes that the wind flow around a building may have adverse effects on the installed green roof system. Similar to the roof regions denoted by ASCE-7, the FLL Standard recognizes regions set forth by the DIN 1055-4 – Structural Design Loads – Part 4: Wind Loads. Because of the increased susceptibility to wind damage at the corners, and edges of a roof, the FLL Standard specifies that gravel or paving slabs should be used in lieu of green roof material in these regions. While green roofs are designed to minimize the substrate depth and dead load resulting from green roof systems, because they are ballasted systems with no rigid connections to secure loose-laid roofing layers, situations where high wind loads occur require the usage of increased substrate depth and/or heavier materials. The FLL Standard states that the critical factor in this determination is the dry load of the layered green roof system ((FLL), 2008).

In general, the wind load design for a green roof system according to the FLL requires first calculating the roof wind loads utilizing the DIN 1055-4 in combination with the coefficient of wind action found in DIN 1055-100 – Structural Design Loads – Part 100 Fundamentals for planning – Safety Concepts and Measuring Standards. The suction loads from these calculations will be used to determine the necessary green roof load to protect against uplift. The suction load, however, experiences a reduction due to various factors associated with green roofs shown below ((FLL), 2008):

- Coarseness of the vegetation
- Load generated by residual moisture in the soil
- Load generated by the vegetation
- Bonding of the layers through the action of the roots in comparison to loose material
- Wind permeability of the vegetation support layer, which diffuses the pressure differential between the top and bottom of the vegetation layer

The DIN 1055-4 prescribes an aerodynamic coefficient for the outside pressure of $Cp_e = 10$, that would be multiplied with the velocity pressure.

Section 14 of the FLL presents erosion control methods, summarized by **Table 4** above.

4.1.3 Plant design and selection

The FLL Standard also incorporates a comprehensive plant design guide based on the intended function for the green roof (e.g. promotion of increased open space, ecology, or economic and environmental protection) as well as the green roof type (intensive, semi-intensive, or extensive). **Appendix A** was extracted from Subsection 7.2.1 of the FLL, specifying the required substrate depth for a specific type of plant.

Section 11 of the FLL Standard places requirements on various vegetation types (seeds, shoots, perennials, bulbs, shrubs/bushes/woody plants, lawn turfs, and vegetation matting) based on various DIN standards. The requirements range from type of fertilization, root ball height and shape, to type of substrate depending on the type of vegetation being grown. One recurring requirement was that plants were to be propagated within nurseries and not picked from the wild.

The initial portion of Section 12 in the FLL Standard specifies steps needed in the implementation of various vegetation species, such as seeding application rates, bracing for tree/shrub stability, etc. The final subsection presents the acceptance criteria for intensive and extensive green roof systems. These acceptance criteria are defined within DIN 18916 – Vegetation Engineering in Landscaping: Plants and Planting and DIN 18917 – Vegetation Engineering in Landscaping: Lawns and Seeding. For extensive systems, sites are handed over only after the plants have gone through a dormant phase and, climate-permitting, experienced a period of drought or frost – a process which takes 12 to 15 months to complete.

Section 13 dictates the maintenance requirements for intensive, semi-intensive, and extensive green roof systems. Extensive systems require maintenance up until 90% coverage, whereas intensive systems require regular maintenance and irrigation.

4.2 FM 1-35

The FM 1-35 was created as a compliance method of determining whether a green roof system could be insured by Factory Mutual. It was first introduced in 2007, but later updated in 2011 to include design specifications from the FLL Standard, and also limit the wind speed restriction for green roofs. The FM 1-35 serves as a general design guideline for green roof systems against various design loads (wind, hail, gravity, seismic), as well as design fire hazards, system maintenance, and proper plant selection. However, like the previous subsection, this portion of the report will summarize the approach that the FM 1-35 takes on addressing the design against wind hazards and the method presented in selecting the proper vegetation.

4.2.1 Wind design

First, the guideline restricts green roof installation to geographic locations where the wind speed (3-second gust, as determined by FM 1-28) is less than 100 mph. This limit was placed to reduce the likelihood of windborne debris generation from either green roof growth media or gravel. It takes a similar approach to the wind design/analysis of the green roof system as the FLL by requiring users to utilize an external wind design guideline (FM 1-28 Wind Design) to calculate the wind design pressures to design a mechanically attached or fully adhered roof membrane system (Global), 2011).

- Subsection 2.2.3.2.2 of the FM 1-35 specifies that the usage of green roof growth media as ballast against wind uplift for the roofing membrane and other waterproofing elements is only acceptable when the uniform substrate depth is at least 8 in. (200 mm). If this depth is fulfilled, a minimum safety factor of 1.7 is applied to the wind uplift calculations to obtain the wind design pressures from FM 1-28. A dry substrate condition with no vegetation is considered to represent the worst-case scenario.
- Subsection 2.2.3.2.3 recommends using clean, smooth, well-rounded stone ballast nominally measuring 1 to 2 in. in diameter, at a depth of at least 3 in.
- Subsection 2.2.3.2.4 allows for green roof growth media to act as secondary ballast material. This means substrate can provide ballast for loose-laid roofing components above the waterproofing membrane but not the membrane itself. A minimum safety factor of 0.85 is used and the same dry condition as 2.2.3.2.2 is followed.

- Subsection 2.2.3.3 prohibits usage of woody vegetation when the wind uplift pressure at the roof elevation is equal to or greater than the uplift pressure at an elevation of 15 ft. or less for ground roughness B and a basic wind speed (3-sec gust) of 110 mph (Global), 2011).
- Subsection 2.2.1 specifies usage of strictly concrete pavers in non-vegetated border zones for buildings over 150 ft. high. For buildings less than 150 ft. high, the usage of either stone ballast or concrete pavers can be used in those regions.
- Subsection 2.2.14.1 specifies that the perimeter and corner zones (border zones) are free of vegetation and growth media. These zones are recommended to:
    1. Provide maintenance access
    2. Provide additional resistance to high wind uplift pressures
    3. Reduce scour of growth media
    4. Reduce potential generation of wind-borne debris at roof perimeters and corners
    5. Provide a fire break at rooftop equipment, penetrations, and structures
- Subsection 2.2.15.2 specifies that this zone must be at least 3 ft. wide in regards to wind and fire hazard mitigation.
- Subsection 2.2.14.3 details the usage of parapet walls. For buildings >150 ft. high, the minimum parapet height is no less than 30 in., whereas for buildings <150 ft. high, parapets are permitted to extend only 6 in. above the top of the growth media, stone ballast, and concrete pavers.
- Subsection 2.2.16.1.5 specifies erosion protection through non-combustible photo-degradable mesh “wind blankets” until vegetation achieves established coverage.

4.2.2 Plant design and selection

FM 1-35 stresses that the critical parameters to consider for the plant selection of a green roof are good fire resistance, good drought resistance, and a non-aggressive vertical root system that reduces the risk of underlying waterproofing layer damage. Selection should still be based off of the local climate, typical green roof species, and also the rooftop microclimate (also specified by the FLL Standard). Plant selection limitations specified by FM 1-35 include (Global), 2011):

- Avoidance of grasses and mosses due to potential fire hazard when dry.
- At least three different species must be used to make up 60% of the vegetation when using groundcover plantings.
- Full-grown, mature height of vegetation must not exceed 3 ft.

4.3 ANSI/SPRI RP-14

In June 2010, the ANSI/SPRI RP-14 was approved as a method of designing the wind uplift resistance of green roof systems. This design guideline focuses solely on the wind design and therefore places no specification to the plant selection of the green roof system. The RP-14 derived directly from the ANSI/SPRI RP-4, and has a guideline layout which closely resembles its predecessor. The document states its limitations (shown in **Table 4**), but defaults the green roof design to qualified professionals when conditions do not meet the guideline specifications. The RP-14’s design procedure for green roof systems, as briefly summarized in **Table 4**, is linked to various gravel ballast wind tunnel studies (Kind and Wardlaw, 1976, Kind and

Wardlaw, 1985), the SIUE study, as well as the ASCE7 Wind Load Provisions. The methodology is specified in Section 6.0 of the RP-14, shown below ((ANSI) and (SPRI), 2010):

1. Determine the geographical location of the building to extract the basic wind speed (3-sec gust, Exposure C at 33 ft. for storms with a 50 year mean recurrence interval, as determined by ASCE7's wind hazard map) and Exposure category.
2. Determine the building height and parapet height. If the building height exceeds 150 ft., the design defaults to a licensed design professional using current wind engineering practices consistent with ASCE7.
3. With the basic wind speed, building height, Importance factor of the structure, and exposure category, utilize the Design Tables provided to select the appropriate System Design (1, 2, or 3).
4. With the System Design determined, find the ballasting requirements based on the type of supporting roof system of the building.
5. Review the design provisions chosen above and provide design enhancements as necessary.

The remainder of this subsection will summarize design specifications specific to this design standard:

- Nominal vegetation coverage is defined as no area greater than a 5 in. diameter of exposed growth media. Systems without nominal coverage are referred to as either Unprotected Growth Media or Unprotected Modular Vegetative Roof Trays. Those with nominal coverage or growth media blow-off mitigation techniques are considered Protected Growth Media or Protected Modular Vegetative Roof Trays.
- Corner regions of the roof have side dimensions equal to 40% of the roof, and must be at least 8.5 ft. in width.
- Edge/perimeter regions of the roof must also have widths equal to 40% of the roof or 8.5 ft., whichever greater.
- Buildings with an Importance factor Category III or IV, or located within Exposure D conditions shall be designed to withstand wind speeds equal to 20 mph greater than the basic wind speed determined by the ASCE 7 wind map. This increased wind speed will be used for the design tables.
- Growth media not nominally covered will be protected with wind erosion prevention techniques such as erosion blankets and liquid binders
- No. 4 ballast can exist as:
    - Growth media at minimum dry weight of 10 psf
    - Interlocking, contoured fit or strapped-together green roof modules/trays with minimum dry growth media weight of 10 psf
    - Green roof modules/trays with minimum dry weight of 18 psf
    - River bottom or coarse stone nominal 1.5 in. of ballast gradation size #4 spread at minimum of 10 psf
    - Independently set concrete pavers with minimum weight of 18 psf
    - Interlocking, beveled, doweled, or contour-fit lightweight concrete pavers (minimum 10 psf)
- No. 4 ballast can exist as:
    - Growth media at minimum dry weight of 13 psf

    - Interlocking, contoured fit or strapped-together green roof modules/trays with minimum dry growth media weight of 13 psf
    - Green roof modules/trays with minimum dry weight of 18 psf
    - River bottom or coarse stone nominal 2.5 in. of ballast gradation size #2 spread at minimum of 13 psf
    - Independently set concrete pavers with minimum weight of 22 psf
    - Interlocking, beveled, doweled, or contour-fit lightweight concrete pavers (minimum 10 psf)
- For Ballasted Vegetative Roofing Systems (where the green roof provides uplift resistance for roofing systems that are not adhered or mechanically attached to the roof deck):
    - System 1: Installed membrane ballasted with #4 ballast as defined above
    - System 2: Corner area with #2 ballast, Perimeter with #2 ballast, Field with #4 ballast (#2 ballast if geographically located in wind-borne debris areas)
    - System 3: Corner and perimeter areas with no loose stone, growth media or modular vegetative roof trays placed on the membrane. Membrane will be adhered or mechanically attached to withstand uplift forces as specified by ANSI/ASCE 7 or local building code in these two regions. If protective covering is required in these two regions, a fully adhered membrane system shall be used installed with minimum 22 psf pavers. Field will be installed with #2 ballast.
- For Protected Vegetative Roofing Systems (insulation installed over waterproofing membrane):
    - System 1 & 2 as above
    - System 3: The insulation installed shall be ballasted with pavers or other approved material at a minimum weight of 22 psf. A minimum parapet height of 24 in. will also be required to use the design tables.
- For Vegetative Roofing Systems Using a Fully Adhered Membrane Roofing System:
    - System 1, 2, & 3 as for the Ballasted case
    - The wind speed allowed for System 1 & 2 shall be increased by 10 mph off of the design tables ((ANSI) and (SPRI), 2010)

4.4 Summary

In evaluating the design standards in this section, it was apparent to the investigators that a recurring trend exists between the FLL Standard, FM 1-35, and RP-14. All three guidelines recognize that the corner and edge regions of a roof experience the highest negative pressures, and therefore specify that no vegetation be placed in those areas. The use of concrete pavers or gravel ballast in these regions to provide adequate uplift resistance was also common between design guidelines. This overall observation was expected based off of the literature reviewed in Section 2.1.

While the FM 1-35 seemed to stem its plant selection methods from the FLL Standard, it can be concluded that the regional climate will play a predominant role in determining a suitable plant selection. As reinforced by the FLL Standard, the investigators of this report are interested to see what Florida's unique climate/weather effects have on the feasibility of green roofs in the state. Florida not only has drought periods, but also has short, intense deluges during its rainy seasons.

Combined with high wind hazards during the summer, plant selection may further be limited as the number of failure parameters increase. This will be addressed later in the report in the bulk of the investigators' studies.

A major limitation in utilizing RP-14's wind design method was dependent upon the ASCE 7-05 wind map included in the document. One fundamental change from ASCE 7-05 to ASCE 7-10 was that the wind speed map from the 2005 edition was split into three separate wind speed maps based on the Risk Category of the buildings (I, II, III & IV). Therefore, the wind speeds in ASCE 7-10's maps are substantially higher than those specified in ASCE 7-05. The change between ASCE 7-05 and ASCE 7-10 simply removed the step of multiplying the obtained wind map speed by an importance factor which increased the loads for Categories III & IV and reduced loads for Category I. The wind speeds on their respective maps in ASCE 7-10 can be used directly in determining the load (Smith, 2010). This would not have posed a problem if the design tables in RP-14 were reflective of ASCE 7-05's bare wind speed map. With an upper limit of 140 mph, almost half of Florida could not use the RP-14 for the wind uplift design of green roof systems since the ASCE 7-10 wind map for Risk Category II Buildings in Florida has 140 mph wind speeds up through Highlands, FL. A possible solution to this would be to apply a 0.6 factor to ASCE 7-10 wind speeds to convert the wind speed from ASCE 7-10's strength design method to ASCE 7-05's allowable stress design.

THIS PAGE IS LEFT BLANK INTENTIONALLY

5. WIND TESTING STUDIES

Following the literature review conducted in 2010, the investigators planned for full-scale wind testing of various green roof systems. From the SIUE study, the scour behavior of a single green roof modules were well documented, but the possibility of green roof uplift failure was still unknown at that study's conclusion. For this reason, the investigators were interested in obtaining comprehensive results on how green roof systems respond to wind flow highly affected by the presence of a building (bluff-body effects). This would require the construction of a mock-up structure that would attempt to mimic/simulate that bluff-body wind effect. In this section, the machinery and equipment utilized to run the full-scale wind tests will be detailed, and the methodology for and summary of results obtained from each phase of wind testing will be provided.

5.1 UF's Hurricane Simulator

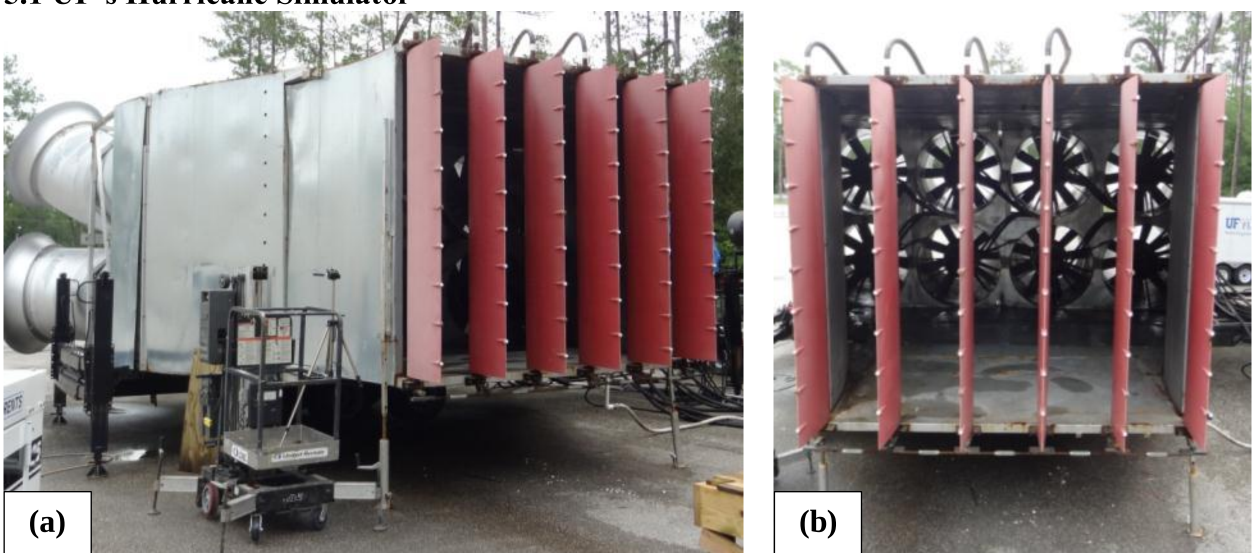


Figure 7. **(a)** Isometric view of hurricane simulator. **(b)** Frontal view of hurricane simulator. **(c)** Back view of simulator's flow diffusers.

The University of Florida developed a portable hurricane simulator in 2007 capable of producing up to 120 mph winds – equivalent to a Category 3 hurricane. **Figure 7** above portrays three different views of the hurricane simulator. The simulator consists of eight (8) 5 ft. diameter fans powered by four (4) 700-HP diesel engines. A 5,000 gallon water tanker is used to cool the engines during testing. The simulator's wind flow opening measures 10 ft. wide x 10 ft. high, and is raised 3 ft. above the ground. The longitudinal turbulence intensity at the testing roof height (≈ 8 ft.) is approximately 5-6%. This value increases as the distance to the ground decreases, as should be expected.

5.2 Test procedures

This subsection summarizes the general test procedures between the two phases of wind testing and the fundamental changes made for Phase 2.

5.2.1 Phase 1 description

Figure 8. General test setup for Phase 1 wind testing.

Wind testing in Phase 1 consisted of six (6) different trials with 54 green roof modules conducted over a series of 6 months (August 2011 – February 2012). Each trial consisted of eight (8) planted modules and a single unplanted module, set in a 3x3 array. The unplanted module's location would be varied between test trials. The intensive modules were 8 in. deep x 24 in x 24 in. while the extensive modules were 4 in. deep x 24 in. x 24in. These modules contained 6 different types of plant species. The wind speeds were varied at 20, 30, 50, 70, and 90 mph for 30 seconds each, and a final 120 mph run at 2 minutes. An RM Young Anemometer was used to verify these wind speeds in the first three trials. The test structure was approximately 8 ft. high x 7 ft. x 7 ft., and included a 12 in. high x 6 in. wide parapet which spanned the perimeter of the structure. The wind direction was normal to the windward wall of the structure.

Test day 1 took place on August 18, 2011 (**3 months establishment**), included a full perimeter parapet and tested three sets of 4 in. modules (4" – T1, 4" – T2, 4" – T3) and one set of 8 in. modules (8" – T1).

Test day 2 took place on October 20, 2011 (**5 months establishment**), and had the same test method and setup as Test day 1, with one set of 8 in. modules (8" – T2).

Test day 3 took place on February 16, 2011 (**9 months establishment**), had the leeward parapet wall removed, and tested 8 in. modules (8" – T3).

Phase 1 of the wind tests utilized visual documentation through two (2) high speed cameras focused on the profile view and one (1) high definition camcorder on top of the simulator. The modules were also weighed before and after wind testing with a single-point hanging load cell (Prevatt, et al., 2011). Results from Phase 1 will be explicitly published in a separate document. This research report will merely review and compare Phase 1 results with those obtained in Phase 2.

5.2.2 Phase 2 description

Figure 9. (a) Test structure from view of one-person scissor lift in Phase 2 wind testing; **(b)** View of test setup from ground.

Further full-scale wind testing in Phase 2 attempts to compare various parameters' effects on green roof systems. The test structure was placed 12 ft. away from the center of the simulator. However, the parapet wall was removed, and the test structure was oriented at a 45° angle to simulate the worst-possible conditions as suggested by the literature in Section 2.1. The walls were 5 ft. tall, and anchored to a deck that was raised 3 ft. off the ground, just under the wind flow area of the hurricane simulator. By orienting the walls at 45°, it was deemed suitable to utilize only two walls to obtain the flow effects desired. With the effects of various wind speeds known from Phase 1, Phase 2 was conducted at 90-100 mph winds (measured for each test trial with an RM Young Anemometer). The test duration was lengthened from 5 minutes to a total of 10 minutes for the majority of the test trials. Four test trials will explore the effects of prolonged exposure to high wind forces at 20 minutes in duration. A new parameter that was introduced to the BIP tests was the presence of high moisture levels in comparison to normal moisture levels observed in the substrate from the growth site's irrigation system.

Phase 2 was initiated in two parts: eight (8) test trials on Built-in-Place (BIP) green roof systems and eight (8) test trials on modular tray green roof systems for a total simulator operation time of 200 minutes.

5.2.2.1 Built-in-place green roof wind tests

The BIP green roof specimens were built in accordance to the manufacturer's specifications. Construction of the BIP trays was completed on April 21, 2012. Four monoculture trays (N-S1, N-S2, N-T1, N-T2) were planted on April 25, 2012, and the remaining four monoculture trays were planted on April 28, 2012 (S-S1, S-S2, S-T1, S-T2). Testing during the week of June 11, 2012 allowed for 7 weeks of growth for the first set of monoculture trays, and 6.5 weeks of growth for the second set of trays. The manufacturer recommended at least 6-8 weeks establishment before wind testing. The BIP test matrix is shown in **Table 5** below.

Table 5. Test Matrix for BIP Systems

Test ID	Plant Date	Wind Testing Date	Establishment Period	Moisture	Plant Species	Plant Height	Continued Testing?
S-M1**	N/A	06/12/2012	N/A	Wet	A, J, L, M, N	Mixed	No
N-S1	04/25/2012	06/12/2012	7 weeks	Normal	N	Short	No
N-S2	04/25/2012	06/13/2012	7 weeks	Normal	A	Short	No
N-T1	04/25/2012	06/12/2012	7 weeks	Normal	M	Tall	No
N-T2	04/25/2012	06/13/2012	7 weeks	Normal	L	Tall	No
S-S1	04/28/2012	06/13/2012	6.5 weeks	Wet	N	Short	No
S-S2	04/28/2012	06/13/2012	6.5 weeks	Wet	A	Short	No
S-T1	04/28/2012	06/19/2012	7.5 weeks	Wet	M	Tall	Yes*
S-T2	04/28/2012	06/19/2012	7.5 weeks	Wet	L	Tall	Yes*
A – *Aptenia cordiflora* "Baby Sunrose" J – *Gaillardia aristata* "Blanketflower" L – *Bulbine frutescens* "Stalked Bulbine"			M – *Lantana camara* "Yellow Bush Lantana" N – *Portulaca grandiflora* "Rose Moss"				

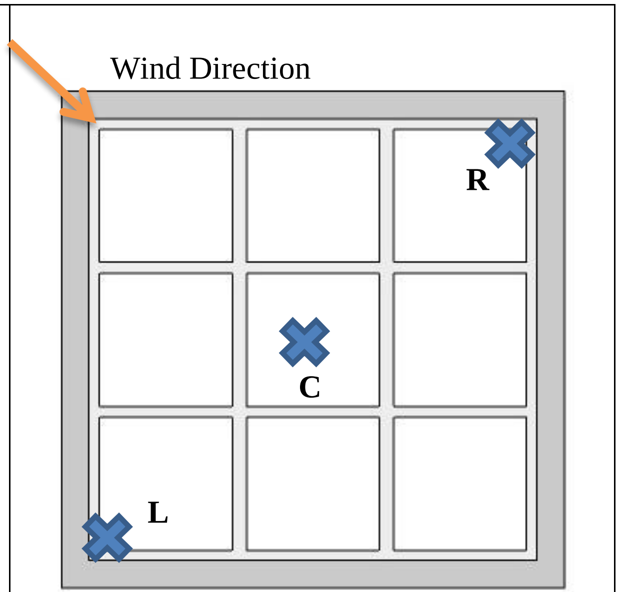
* Continued testing will explore the coverage ratio effects as testing is prolonged from 10 minutes to 20 minutes (4-5 minute intervals). Overhead photography will be obtained before testing, and after each 10 minute interval. The trials chosen represent the worst-case scenarios out of the test matrix.

** This trial was a test run to note any problems or errors during operation, and also determine the best approach to each test trial

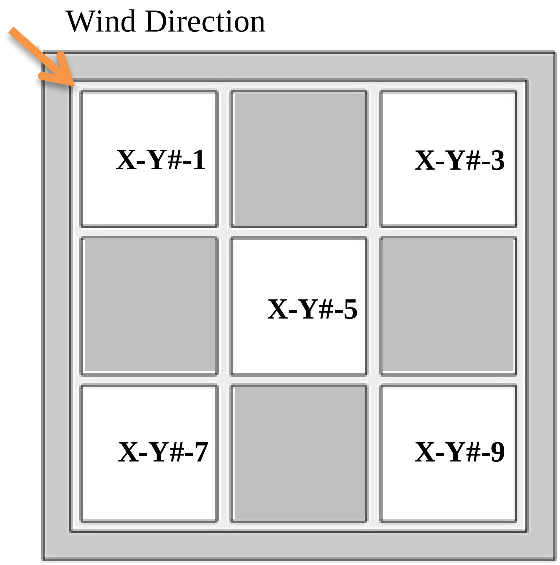
5.2.2.1.1 Procedure

The step-by-step procedure for each BIP tray test trial will be as follows (not including "continued testing" trials).

Step	Description	Photo
1	Transport BIP tray with forklift to photography station	
2	Take overhead photo noting wind direction and tray ID	
3(a)	If tray is specified as highly saturated, install three rain gauges as detailed in Step 3(b). Attach sprinkler nozzle, irrigation pump, and water until a full 55 gallon barrel is emptied. The time at which the barrel empties is recorded.	

3(b)	Rain gauges are to be installed across the diagonal of the designated BIP specimen (illustrated by the X's on the adjacent figure)	
4	Raise and place on test structure. Seal gaps between BIP tray and walls with backer rods and aluminum flashing.	
5	Run simulator for 5 minutes at 100 mph. Have two profile view cameras recording at real-time and high-speed, one aerial view HD camcorder. The time testing initiates is recorded.	
6	After first 5 minute segment, observe any areas of interest (high scour, plant failure, etc.) and take spot photos	

7	Run simulator for 2nd 5 minute segment at 100 mph with the same camera setup as Step 5. The time testing initiates is recorded.	
8	Place BIP tray on photography station, and repeat Step 2.	
9(a)	Take soil samples at the 5 specified locations (as further specified in step 9(b)). These samples are stored in a cooler until tested. The time the samples are taken is recorded.	

<table>
<tr><td>9(b)</td><td>The five (5) sample locations were the four (4) corners and the center of each specimen. The moisture contents of each of these locations were then averaged to provide a more accurate representation of the BIP specimen.</td><td>

where,
X = “N” for Normally Saturated or “S” for High Saturation
Y = “T” for Tall plant species or “S” for Short plant species
# = “1” or “2,” depending on which of the tall/short plant species</td></tr>
<tr><td>10</td><td>Return BIP tray to growth site</td><td></td></tr>
</table>

Post processing of the video data will focus on plant failure and scour patterns given the duration of testing. Soil samples were sent to UF’s Soils and Water Sciences Department for moisture content analysis. Overhead photos will be processed via Adobe Photoshop CS3, as detailed in **Appendix B**.

5.2.2.2 Modular tray green roof tests

Modular tray green roof tests will be conducted in a similar fashion as Phase 1 wind testing. The 12 month modules were planted in May 2011, while the 6 month modules were planted at the end of December 2011. After the first phase of testing, it was perceived that plant height plays a large part in green roof survivability. Therefore, the plant design in December aimed to isolate the tall species (T7, T10) from the short species (T8, T11). An addition to the previous test procedure is the collection of soil samples to determine the moisture content of the growth substrate. Special care should be taken to place previously tested 12 month modules in the same exact position in the 3x3 grid as Phase 1 wind testing. **Table 6** below shows the proposed test matrix for modular tray green roof wind testing.

Table 6. Test matrix for modular tray green roof systems

Test ID	Wind Testing Date	Establishment Period	Media Depth	Plant Height	Plant Species	Continued Testing?
T2	06/18/2012	12 months	4”	Mixed	A, B, C, D, E, F	No
T3	06/18/2012	12 months	4”	Mixed	A, B, C, D, E, F	No
T5	06/20/2012	12 months	8”	Mixed	A, B, C, D, E, F	No
T6	06/20/2012	12 months	8”	Mixed	A, B, C, D, E, F	No
T7	06/21/2012	6 months	4”	Tall	B, G, G, H	Yes*
T8	06/20/2012	6 months	4”	Short	D, I, J, K	No
T10	06/22/2012	6 months	8”	Tall	A, G, G, H	Yes*
T11	06/22/2012	6 months	8”	Short	I, J, K	No

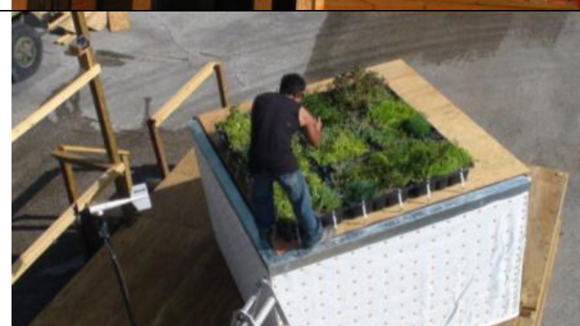
A – *Aptenia cordiflora* “Baby Sunrose”
B – *Delosperma cooperi* “Ice Plant”
C – *Dianthus grantianopolitanus* “Dianthus”
D – *Lantana montevidernsis* “Trailing Lantana”
E – *Salvia rutilans* “Pineapple Sage”
F – *Sedum rupestre* “Angelina Sedum”
G – *Sedum rupestre* “Lemon Coral”
H – *Delosperma nubigenum* “Yellow Ice Plant”
I – *Rosmarinus offcianalis* “Rosemary”
J – *Gaillardia aristata* “Blanketflower”
K – *Coreopsis lanceolata* “Sunray”

* Continued testing will explore the coverage ratio effects as testing is prolonged from 10 minutes to 20 minutes (4-5 minute intervals). Overhead photography will be obtained before testing, and after each 10 minute interval. The trials chosen represent the worst-case scenarios for each plant height.

5.2.2.2.1 Procedure

The step-by-step procedure for each modular green roof test trial will be as follows (not including "continued testing" trials).

Step	Description	Photo
1	Weigh modules on digital scale and photograph. The time the initial weighing is conducted is recorded.	
2	Place on bare deck on photography station and note location and wind direction. Take overhead photograph.	
3	Following Test Trial T8, the leading edges of the two windward rows of modules were tethered to the bare deck with zip-ties and eye screws. Modules were also zip-tied to each other in accordance to the manufacturer's request	

4	Raise deck frame to height on structure with forklift. Position manually until snug. Seal with backer rods	
5	Run simulator for 5 minutes at 100 mph. Have two profile view cameras recording at real-time and high-speed, one aerial view HD camcorder. The time testing initiates is recorded.	
6	After first 5 minute segment, observe any areas of interest (high scour, plant failure, etc.) and take spot photos	
7	Run simulator for 2^{nd} 5 minute segment at 100 mph with the same camera setup as Step 5. The time testing initiates is recorded.	
8	Remove deck frame and place on photography station. Take overhead photograph, noting wind direction	

9	Remove modules from deck frame, reweigh, and record. Photograph each module. The time the post-test weighing is conducted is recorded.	
10	Take soil sample from center of each module, place in Zip-Loc bag, and store in cooler. The time the samples are taken is recorded.	

Post processing of the video data will focus on plant failure and scour patterns given the duration of testing. Soil samples were sent to UF's Soils and Water Sciences Department for moisture content analysis. Overhead photos will be processed via Adobe Photoshop CS3, as detailed in **Appendix B**.

5.3 Results

This section of the report summarizes the wind testing results obtained from the first and second phase of testing. Results will be divided into the two different types of green roof systems that were explored for this research study: modular tray green roof systems and BIP green roof systems. For Phase 2, the wind speed target of 100 mph was achieved by throttling the engines up to 2000 rpms, where the speed fluctuated from 100 mph +/- 5%.

5.3.1 Modular tray green roof systems

The modular tray green roof systems were tested in both Phase 1 and Phase 2 of the research study, allowing for in depth investigation on plant establishment performance against wind forces, as well as recovery potential of any plants that failed. For the retested 12-month modules in Phase 2, the investigators maintained the specimen's original locations within their respective test arrays in Phase 1. However, after the observed performance of the modular specimens in Phase 1, significant changes in the testing methods were made for Phase 2. These changes are described in Section 5.2 above and summarized as follows:

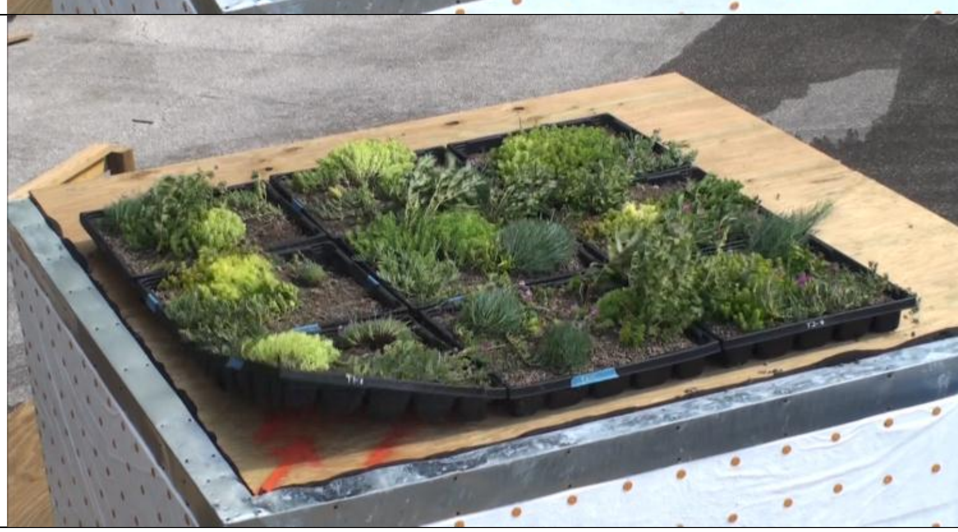
- Wind direction changed from normal to the ridge to cornering wind
- Parapet wall was completely removed
- Wind tests had much longer durations, with a single sustained wind speed
- Nonvegetated modules were not utilized
- Soil samples were collected at the end of each trial

5.3.1.1 Failure of specimen sets T3 and T8

Complete failure of the modular tray green roof systems was observed on two separate occasions in Phase 2: Test Trial T3 on 6/18/2012 and Test Trial T8 on 6/20/2012. Following the failure of specimen set T3 on 6/18/2012, the investigators consulted with the manufacturer who advised zip-tying the individual modules together with a minimum of two (2) 120-lb tensile capacity, UV-resistant plastic cables. Specimen set T3 had individual module failures while T8 suffered complete failure of the entire system.

Both sets of test specimens had a nominal substrate depth of 4 inches and failed due to the initial uplift of the leading corner module. Specimen sets T3 and T8 both failed at 22 seconds and 20 seconds, respectively, after the engines reached the 2000 rpm target. The following subsections will provide step-by-step visual accounts from the aerial and profile views for specimen sets T3 and T8 during their failure.

5.3.1.1.1 T3 failure

	Description	**Aerial Vantage Point**
1	At t = 0 s, the plants have not been exposed to any wind forces.	
2	At t = 22 s, Module T3-8 in the leading corner initiates uplift.	

3	The module is completely airborne within less than 1 second, and impacts several others on the test structure.	
4	Modules T3-3 and T3-5 are now airborne due to initial impact. Other modules have been shifted about the deck.	
5	Module T3-6 slides off the leeward corner of the deck.	

6	Finally, Module T3-9 initiates uplift and blows off of the deck. Total time for failure was under 2 seconds. The remaining four (4) modules stay atop the deck.	

5.3.1.1.2 T8 failure

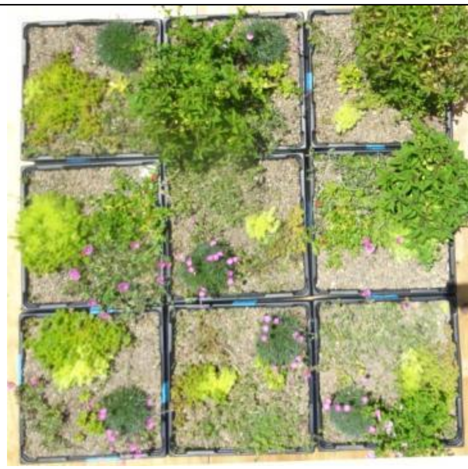
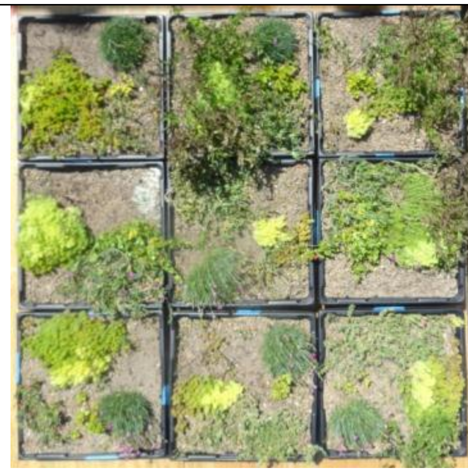
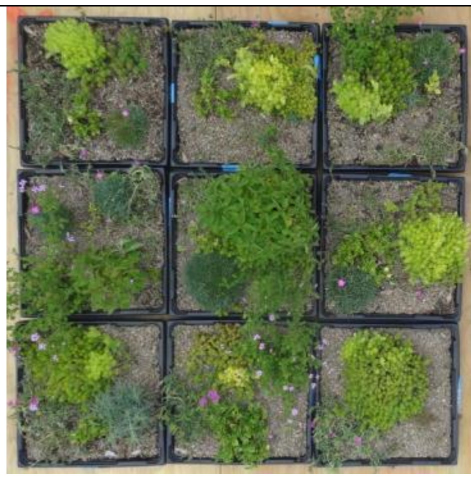
	Description	Aerial Vantage Point
1	At t = 0 s, the plants have not been exposed to any wind forces.	
2	At t = 20 s, Module T8-7 in the leading corner initiates uplift.	

3	The entire system now initiates uplift.	
4	The entire system is blown off the roof. Failure occurs in less than one (1) second.	

5.3.1.2 Scour characteristics

Overhead photography was taken of each set of the modular tray green roof specimens before, 10 minutes after, and 20 minutes after wind testing (if applicable). As detailed by **Appendix B**, the coverage ratio was calculated using Adobe Photoshop. **Tables 7a & 7b** below summarizes the coverage ratios obtained. Wind direction in all of the following photos originate from the top left corner of each figure.

Table 7a. Coverage ratio comparison of modular tray green roof specimens subject to 10 minutes of wind testing.

Module Set ID	Before	After 10 Minutes
T2	 **64.50%**	 **61.24%**
T3	 **59.67%**	**No Photo Taken - Premature Failure**
T5	 **87.58%**	 **70.36%**

T6	 **63.17%**	 **64.71%**
T8		**No Photo Taken - Premature Failure**
T11		

Table 7b. Coverage ratio comparison of modular tray green roof specimens subjected to 20 minutes of testing

Module Set ID	Before	After 10 Minutes	After 20 Minutes
T7			
T10			

5.3.1.3 Biomass loss

Biomass loss in the form of plant leaves, stems, flowers, or even entire plants were monitored during and between wind test trials by the researchers' personal observations. Further footage review will allow for determination of specific plant failure locations, as well as degree of damage the plants experienced. **Table 8** below will provide a general indication of plant loss during each test set of modular tray green roofs.

Table 8. Biomass loss observations for modular tray green roof wind tests

		5 Minute Observation Segments			
Test ID	**Plant Height / Substrate Depth**	**First**	**Second**	**Third**	**Fourth**
T2	Mixed / 4"	Some plant loss observed.	No losses observed.	-	-
T3	Mixed / 4"	Loss of some leaves observed before failure.	-	-	-
T5	Mixed / 8"	Some plant debris loss observed. A lot of leaves were absent on leeward corner module.	Small plant debris loss, but no full plants. Leeward corner module has wilted leaves at end of testing	-	-
T6	Mixed / 8"	Taller plants bend over aluminum edge restraint. Dianthus exposed substrate.	Salvia and Lantana regained structural integrity by 2nd segment.	-	-
T7	Tall / 4"	Gaillardia bent over apparent. Leading corner plants are bare of leaves.	Plants remain bent over.	None	None
T8	Short / 4"	None before failure.	-	-	-
T10	Tall / 8"	Plants all bend downwards. Full plant loss was observed four (4) minutes into the 1st segment. Stem lodging is observed (broken stems).	No losses observed.	No losses observed.	No losses observed.
T11	Short / 8"	Small plant seen as windborne debris. No plant stresses observed from ground.	No losses observed.	-	-

5.3.1.4 Moisture content and weight loss

Moisture content from each green roof module was taken after wind testing. The results are summarized in **Table 9** below.

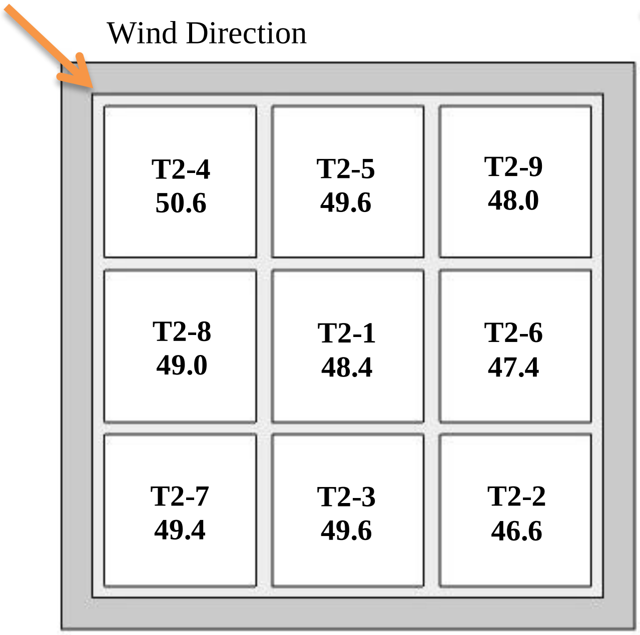
Table 9. Percentage weight change and moisture content of modular tray green roofs

Specimen ID	Specimen Location	Pre-Test Weight (lbs)	Post-Test Weight (lbs)	% Loss	Moisture Content After Wind Testing	Pre-Weight Total (lbs)	Post-Weight Total (lbs)	Total Weight Change (lbs)
T2-1	5	48.4	47.4	-2.1%	20.75%	438.6	423.4	-15.2
T2-2	9	46.6	45.4	-2.6%	17.14%			
T2-3	8	49.6	48.2	-2.8%	21.83%			
T2-4	1	50.6	48.8	-3.6%	23.02%			
T2-5	2	49.6	47.6	-4.0%	24.49%			
T2-6	6	47.4	45.4	-4.2%	23.52%			
T2-7	7	49.4	49	-0.8%	21.83%			
T2-8	4	49	44.8	-8.6%	20.77%			
T2-9	3	48	46.8	-2.5%	18.49%			
T3-1	4	49.2	No Data Available – Premature Failure					
T3-2	3	48.6						
T3-3	5	48.6						
T3-4	7	51.6						
T3-5	6	47.8						
T3-6	9	47.2						
T3-7	8	46						
T3-8	1	54.8						
T3-9	2	40.6						
T5-1	9	84.6	83.4	-1.4%	10.98%	813.2	807.4	-5.8
T5-2	5	89.2	88.6	-0.7%	20.98%			
T5-3	8	97.8	97.2	-0.6%	21.52%			
T5-4	4	88.6	88	-0.7%	16.05%			
T5-5	7	86.4	86	-0.5%	26.49%			
T5-6	1	95	94	-1.1%	24.32%			
T5-7	2	89	88.4	-0.7%	10.80%			
T5-8	6	88.2	87.8	-0.5%	15.29%			
T5-9	3	94.4	94	-0.4%	20.37%			

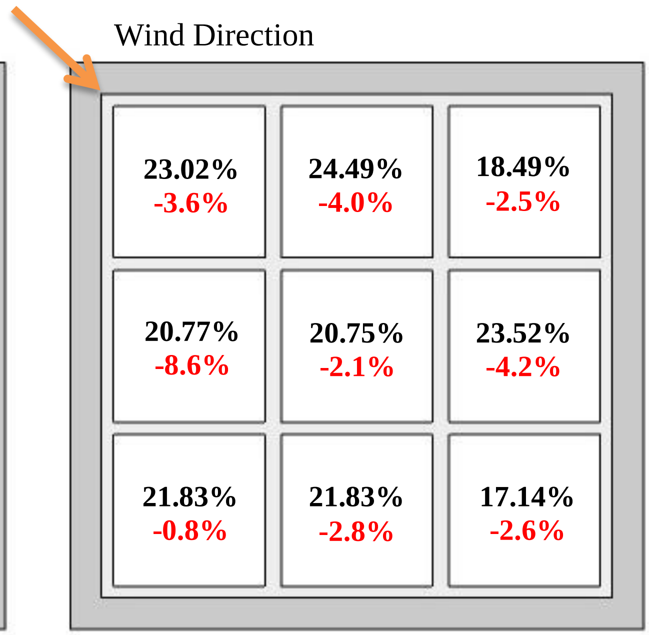
T6-1	4	92.4	91	-1.5%	17.10%			
T6-2	1	101	98.8	-2.2%	25.60%			
T6-3	3	89.4	88.2	-1.3%	20.69%			
T6-4	6	87.6	85.6	-2.3%	20.11%			
T6-5	7	93.2	92.2	-1.1%	24.17%	850	835.6	-14.4
T6-6	5	94.4	92.2	-2.3%	22.25%			
T6-7	2	92.2	90.8	-1.5%	26.03%			
T6-8	9	94.6	92.8	-1.9%	23.19%			
T6-9	8	105.2	104	-1.1%	21.51%			
T7-1	6	47	39.2	-16.6%	23.57%			
T7-2	5	45.6	43.4	-4.8%	23.17%			
T7-3	1	47.2	37.6	-20.3%	27.68%			
T7-4	9	45.4	44.6	-1.8%	25.82%			
T7-5	4	53.8	48	-10.8%	29.97%	426.8	390	-36.8
T7-6	3	49.2	49.6	0.8%	29.35%			
T7-7	8	43.6	40	-8.3%	31.07%			
T7-8	2	42.8	36.8	-14.0%	26.11%			
T7-9	7	52.2	50.8	-2.7%	22.29%			
T8-1	4	35.1						
T8-2	2	46						
T8-3	8	46.3						
T8-4	9	41.4						
T8-5	3	45.6	No Data Available – Premature Failure					
T8-6	5	52						
T8-7	1	54.2						
T8-8	7	51						
T8-9	6	46.2						
T10-1	7	90	89.4	-0.7%				
T10-2	4	92.4	90.8	-1.7%				
T10-3	9	106	105	-0.9%				
T10-4	8	92.2	91.8	-0.4%				
T10-5	6	94.8	95	0.2%		851.4	829.6	-21.8
T10-6	2	82.2	80	-2.7%				
T10-7	1	93	80.4	-13.5%				
T10-8	3	97.2	96	-1.2%				
T10-9	5	103.6	101.2	-2.3%				

T11-1	9	85.6	85	-0.7%		884	876.4	-7.6
T11-2	5	107.4	106.8	-0.6%				
T11-3	8	105.8	105	-0.8%				
T11-4	6	104.4	103	-1.3%				
T11-5	4	105	104.4	-0.6%				
T11-6	1	104.8	104	-0.8%				
T11-7	7	97	96	-1.0%				
T11-8	3	99.8	99.2	-0.6%				
T11-9	2	74.2	73	-1.6%				

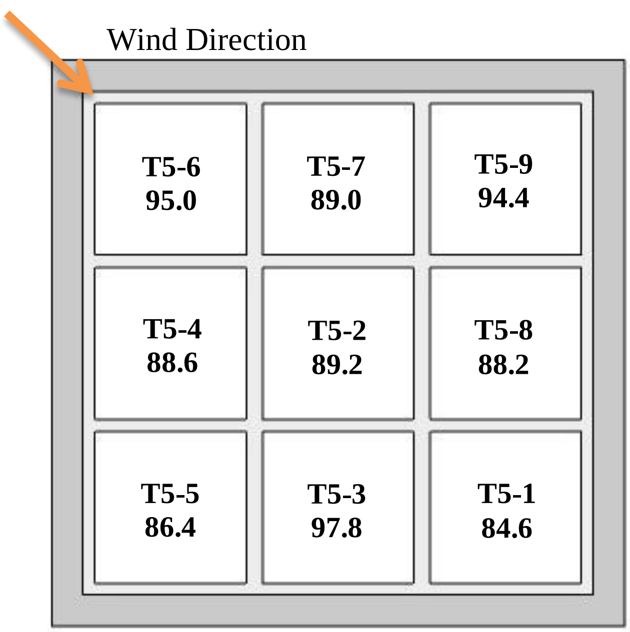
To further illustrate the interaction between percentage weight loss, moisture content, and position in relation to the wind flow, the tabularized data above was placed into 3x3 arrays representing actual placement of module specimens in each test trial. The wind flow direction in these figures is the same orientation as the rest of the report, with the wind originating from the top left corner, illustrated on each figure.



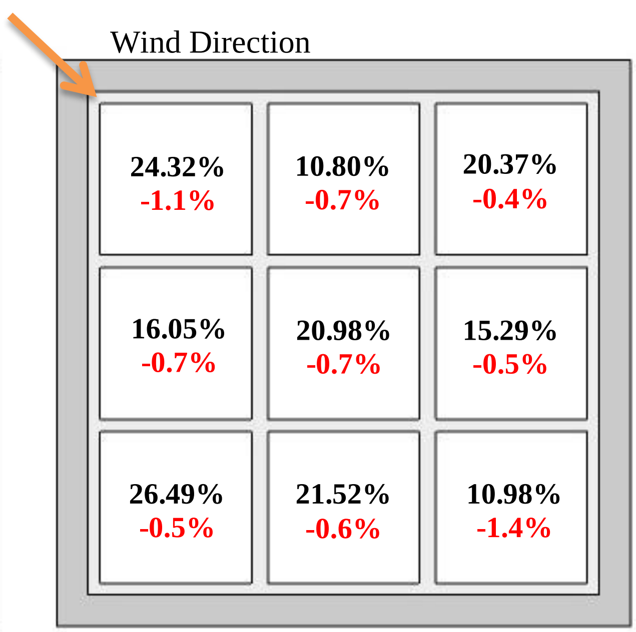
Top: Module ID
Bottom: Pre-Test Weight (lbs)



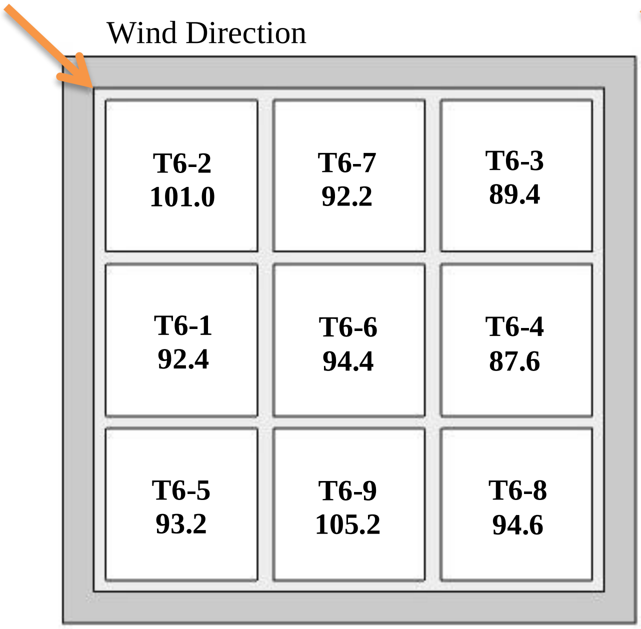
Top: Moisture Content (%)
Bottom: Post-Test Weight Change (lbs)



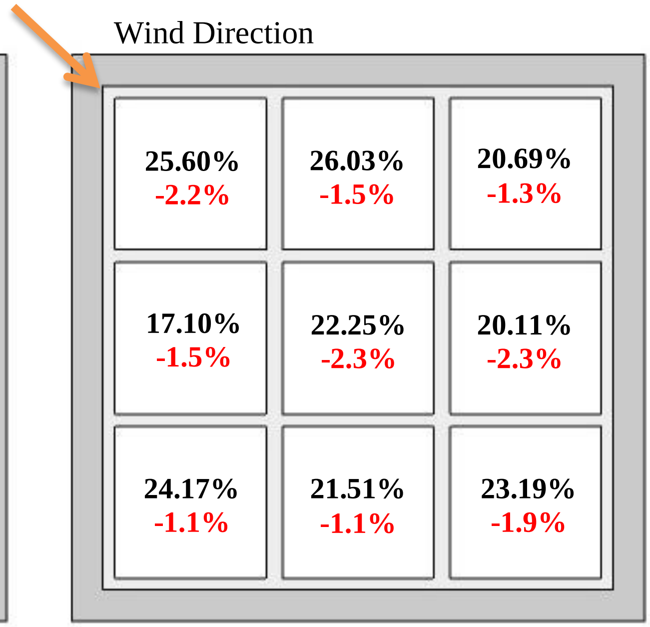
Top: Module ID
Bottom: Pre-Test Weight (lbs)



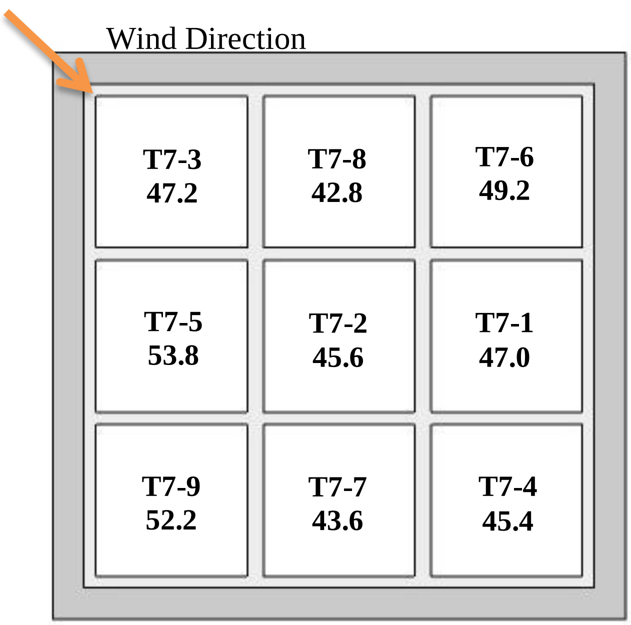
Top: Moisture Content (%)
Bottom: Post-Test Weight Change (lbs)



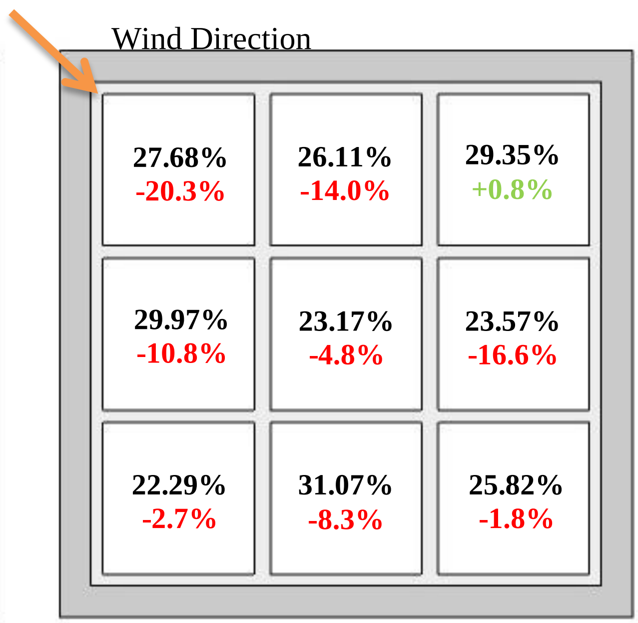
Top: Module ID
Bottom: Pre-Test Weight (lbs)



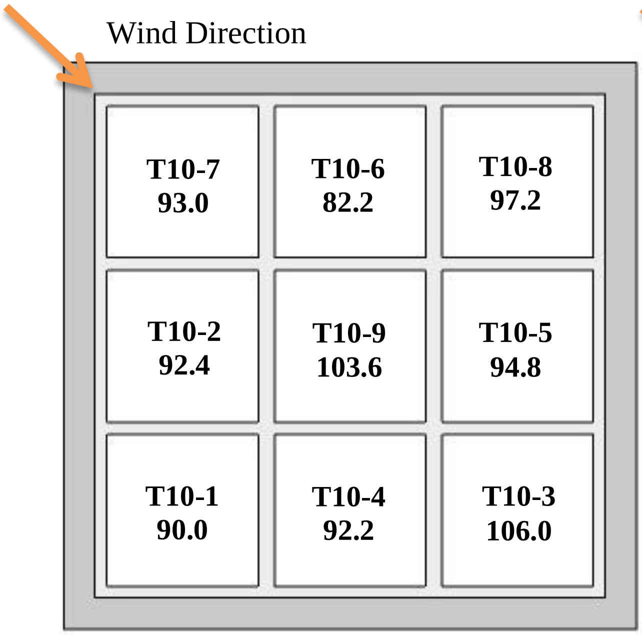
Top: Moisture Content (%)
Bottom: Post-Test Weight Change (lbs)



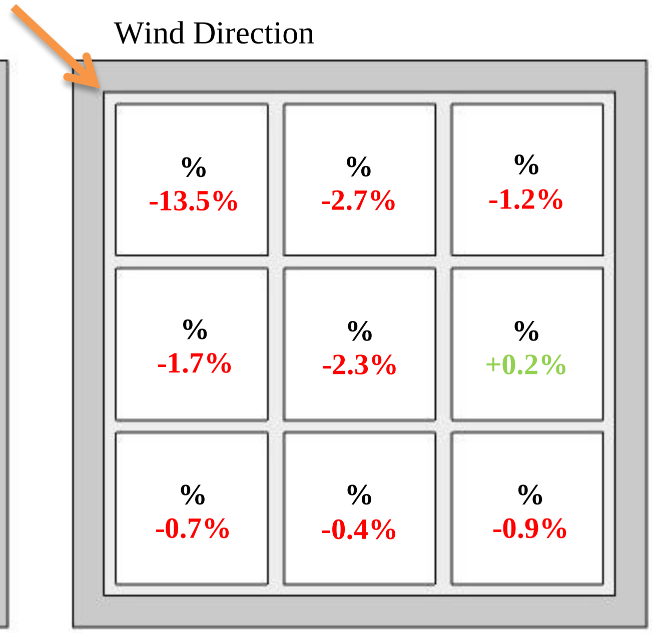
Top: Module ID
Bottom: Pre-Test Weight (lbs)



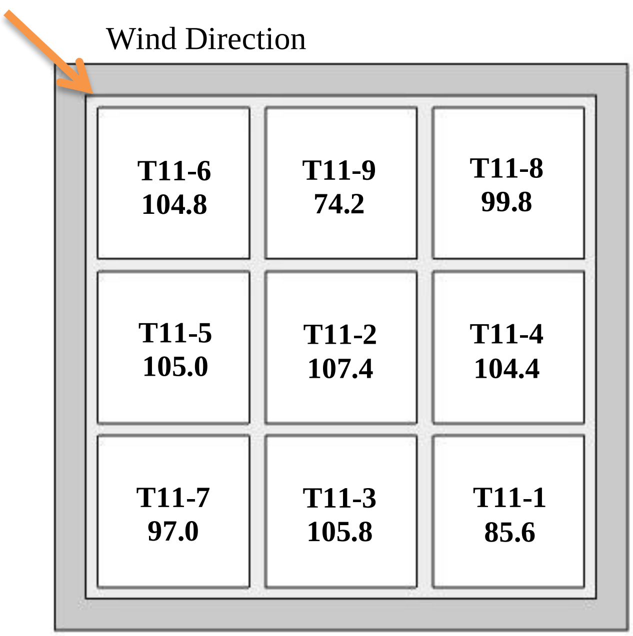
Top: Moisture Content (%)
Bottom: Post-Test Weight Change (lbs)



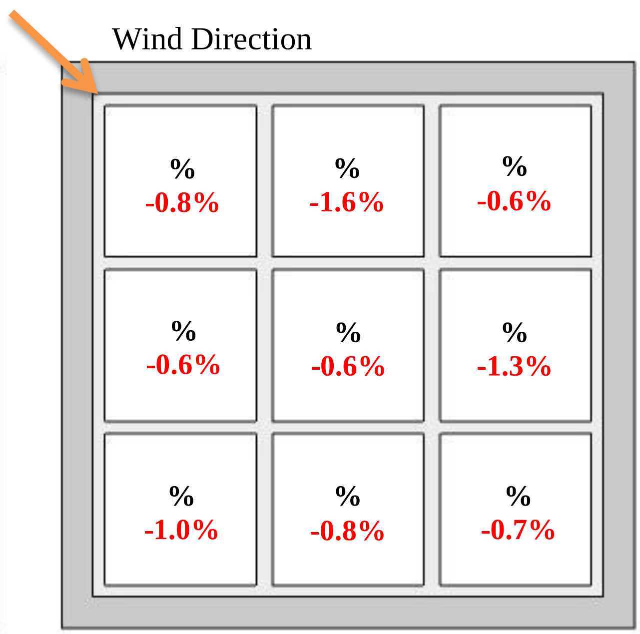
Top: Module ID
Bottom: Pre-Test Weight (lbs)



Top: Moisture Content (%)
Bottom: Post-Test Weight Change (lbs)



Top: Module ID
Bottom: Pre-Test Weight (lbs)



Top: Moisture Content (%)
Bottom: Post-Test Weight Change (lbs)

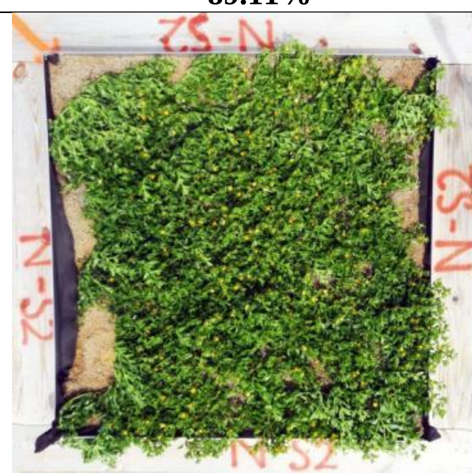
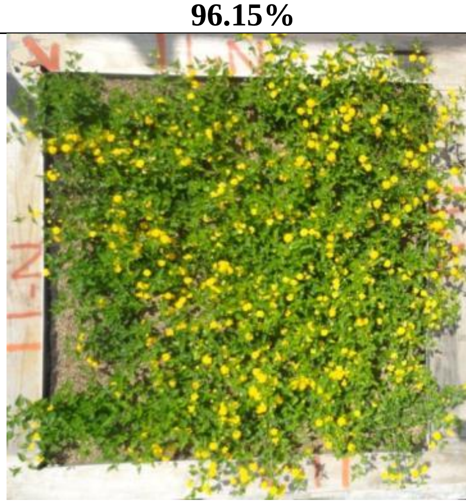
5.3.2 Built-in-place green roof systems

BIP green roofs were also tested in Phase 2 of the study to explore how larger systems of plant monocultures with relatively short establishment periods (6.5 – 7.5 weeks) would respond to high wind forces. The researchers aim to compare the qualitative data obtained by various video recording and personal observations with quantitative data provided by coverage ratio and moisture content determinations.

5.3.2.1 Scour characteristics

Overhead photography was taken of each BIP green roof specimen before, 10 minutes after, and 20 minutes after wind testing (if applicable). As detailed by **Appendix B**, the coverage ratio was calculated using Adobe Photoshop. **Table 10a & 10b** below summarizes the coverage ratios obtained.

Table 10a. Coverage ratio comparison of BIP green roof systems subject to 10 minutes of wind testing.

BIP Module ID	Before	After 10 Minutes
N-S1	 **96.86%**	 **89.11%**
N-S2	 **96.15%**	 **81.09%**
N-T1	 **74.31%**	 **43.61%**

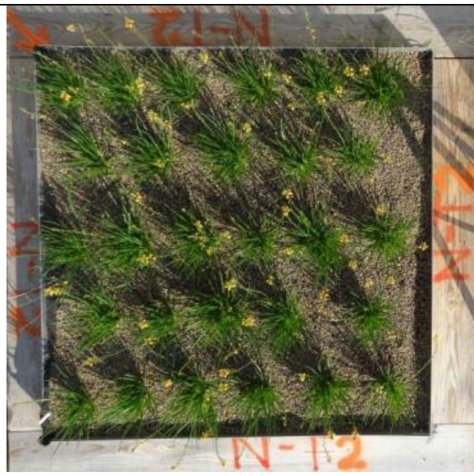
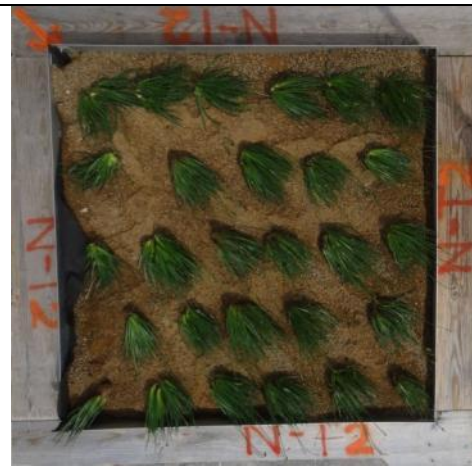
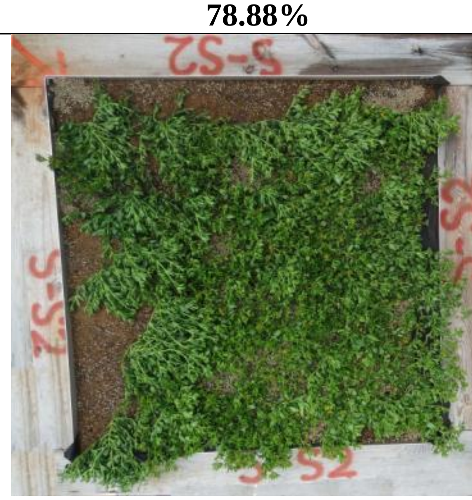
N-T2	 **50.92%**	 **32.39%**
S-S1	 **97.97%**	 **78.88%**
S-S2	 **91.76%**	 **78.09%**

Table 10b. Coverage ratio comparison of BIP green roof systems subjected to 20 minutes of testing

BIP Module ID	Before	After 10 Minutes	After 20 Minutes
S-T1	 94.00%	 68.49%	 56.34%
S-T2	 47.41%	 35.22%	 34.61%

5.3.2.2 Biomass loss

Biomass loss in the form of plant leaves, stems, flowers, or even entire plants were monitored during and between wind test trials by the researchers' personal observations. Further footage review will allow for determination of specific plant failure locations, as well as degree of damage the plants experienced. **Table 11** below will provide a general indication of plant loss during each BIP test trial.

Table 11. Biomass loss observations for BIP green roof wind tests

		5 Minute Observation Segments			
Tray ID	Plant Height	First	Second	Third	Fourth
N-S1	Short	No signs of damage from ground. Plants are seen to displace in shape of wind flow (refer above to **Table 10a**)	No losses observed.	-	-
N-S2	Short	Plants stay relatively still. Windward corner is exposed as plant displaced in direction of wind flow.	No losses observed.	-	-
N-T1	Tall	Small, windborne debris is observed in the form of leaves and flowers. Root lodging is observed as predominant failure mode.	Plant loss is observed approximately 2 minutes into 2nd segment.	-	-
N-T2	Tall	No noted plant structure loss. All plants bend in direction of wind flow. Root lodging on all plants.	No losses observed. Root lodging is magnified.	-	-
S-S1	Short	No losses observed. Plant displacement in direction of wind flow.	Plant loss observed at approximately 3 minutes into 2nd segment	-	-
S-S2	Short	Plants noted to stay relatively still. No losses observed. Plant displacement in direction of wind	No losses observed.	-	-

		flow.			
S-T1	Tall	Plants were observed to bend, but not break off. Root lodging was noted as prominent failure mode.	No losses observed.	No losses observed.	No losses observed.
S-T2	Tall	Three (3) plants were seen to be dislodged immediately. Leaves were observed as windborne debris. Plant loss was identified as originating from leading corner of BIP tray.	No losses observed.	Leaves are seen to be dry and damaged from impact of wind forces. Plants located at the leading edge are noted to be bare of leaves.	No observed losses. Root lodging is prominent along the left windward edge where the highest level of scour is observed.

5.3.2.3 Moisture content

Moisture content of each BIP specimen was obtained as defined in **Step 9(b) of Subsection 5.2.2.1.1**. Because the lead time for setting up, preparing, testing, and extracting the soil samples for each specimen was highly dependent upon external factors such as weather and proper equipment operation, the amount of water sprayed was controlled with the depletion of a single, full 55 gallon barrel, and the time elapsed between barrel depletion and sample collection was also determined. Rain gauges were installed, as defined in **Step 3(b) of Subsection 5.2.2.1.1**. **Tables 12a & 12b** on the following pages summarize the moisture content findings for the BIP specimens. The full moisture content analysis can be found in **Appendix D**.

Table 12a. Moisture content for highly saturated specimens

Tray ID	Rain Gauge Reading L (in.)	Rain Gauge Reading C (in.)	Rain Gauge Reading R (in.)	Barrel Depletion Time	Sample Collection Time	Time Elapsed (min)	Sample ID	Sample % Moisture	Averaged % Moisture for Tray
S-S1	1.1	1.5	0.85	4:56 PM	5:33 PM	37	S-S1-1	24.52%	29.68%
							S-S1-3	31.80%	
							S-S1-5	31.99%	
							S-S1-7	28.59%	
							S-S1-9	31.48%	
S-S2	1.4	1.5	1	3:50 PM	4:36 PM	46	S-S2-1	26.32%	28.92%
							S-S2-3	28.99%	
							S-S2-5	30.27%	
							S-S2-7	28.05%	
							S-S2-9	30.97%	
S-T1	0.6	2.7	0.8	2:15 PM	4:32 PM	137	S-T1-1	20.65%	23.89%
							S-T1-3	22.99%	
							S-T1-5	26.16%	
							S-T1-7	23.00%	
							S-T1-9	26.63%	
S-T2	0.95	1.2	0.25	10:40 AM	1:28 PM	168	S-T2-1	21.89%	25.79%
							S-T2-3	24.54%	
							S-T2-5	25.70%	
							S-T2-7	27.09%	
							S-T2-9	29.73%	

Table 12b. Moisture content for normal saturated specimens

Tray ID	Wind Testing Time	Sample Collection Time	Time Elapsed (min)	Sample ID	Sample % Moisture	Averaged % Moisture for Tray
N-S1	6:29 PM	7:01 PM	32	N-S1-1	21.16%	23.71%
				N-S1-3	24.05%	
				N-S1-5	27.73%	
				N-S1-7	19.99%	
				N-S1-9	25.61%	
N-S2	10:36 AM	11:40 AM	64	N-S2-1	15.02%	21.16%
				N-S2-3	24.78%	
				N-S2-5	24.15%	
				N-S2-7	19.70%	
				N-S2-9	22.14%	
N-T1	5:30 PM	6:10 PM	40	N-T1-1	23.83%	25.47%
				N-T1-3	24.46%	
				N-T1-5	28.57%	
				N-T1-7	24.70%	
				N-T1-9	25.78%	
N-T2	9:49 AM	10:36 AM	47	N-T2-1	21.52%	25.58%
				N-T2-3	28.04%	
				N-T2-5	25.72%	
				N-T2-7	25.86%	
				N-T2-9	26.77%	

5.4 Discussion

5.4.1 Moisture content

Because all of the samples in both the BIP and modular tray green roofs sets were stored outdoors, moisture content was highly dependent upon the weather conditions the day before and day of testing and soil sampling. The following **Table 13** provides the precipitation history of the days during the week and a half of wind testing and soil sampling that was conducted. Testing and soil sampling were conducted in rain-free conditions.

Table 13. Daily rainfall over the testing period (Source: Wunderground.com)

	06/11	06/12	06/13	06/14	06/17	06/18	06/19	06/20	06/21	06/22
Rainfall (in)	0.00	0.02	0.27	2.03	0.00	0.00	0.00	3.96	0.01	0.35
Time	-	4PM	10PM to 11PM	1AM to 2AM; 3:30PM to 7:00PM	-	-	-	7AM to 8AM	3PM	4PM to 7PM

5.4.1.1 Built-in-place green roof systems

The BIP systems were tested and sampled during times with relatively no rainfall. Therefore, the moisture content levels obtained are dependent upon the amount of sun exposure and time elapsed from irrigation to sample collection. It can be seen that the highly saturated specimens exposed to 55 gallons of water resulted in generally higher moisture content percentages than the normally saturated. S-S1 and S-S2 portray a clear distinction that a wetter condition was experienced by the specimens in direct comparisons with their normally saturated counterparts (N-S1 and N-S2). The tall specimens, however, do not provide as direct of a result. Because S-T1 and S-T2 were both tested for 20 minutes as opposed to 10 minutes (as N-T1 and N-T2), a significantly longer time elapsed between initial wetting and sampling time. Knowing this, 55 gallons was still sprayed normally on S-T1 and S-T2. Because the final moisture content between the highly saturated and normally saturated tall plant species are so similar, it cannot be known whether the increased elapsed time allowed for complete drainage of the substrate.

5.4.1.2 Modular tray green roof systems

Modular green roof specimens were subject to normal saturation, and no additional attempts at creating wetter conditions were made. These samples had moisture contents which ranged anywhere from 10% to 30% within a specimen set. A direct correlation could not be made between module depth and measured moisture content.

5.4.2 Scour patterns

Both the BIP and modular green roof system tests shared similar visual characteristics in terms of growth media scour and plant displacement/bending patterns. However, because the modular tray green roof systems essentially discretize a continuous green roof (like a BIP system) into compartmental 2 ft. x 2 ft. modules, localized scouring was more apparent, whereas the BIP tray exhibited globalized scour patterns. Subsections 5.4.1.1 and 5.4.1.2 will discuss the key areas of interest when exploring the scour patterns in the BIP and modular tray green roof systems.

5.4.2.1 Built-in-place green roofs

5.4.2.1.1 Problematic zones and scour direction

BIP green roof systems exhibited extreme scour patterns on the windward edges for all test trials as shown in blue circles below in **Figure 10 (a)**. These edge regions, at times, lost up to Plants appear to bend in the direction of the conical vortices, showing a distinct parallel bending with the windward edges for plants near those edges, whereas plant bending was generally in the direction of the hurricane simulator wind flow when located closer to the leeward corner of the deck (**Figure 10 (b)**). Coarse aggregate that did not blow-off the roof generally was found to build up in three key areas shown below in red circles on **Figure 10 (a)**. It should be noted that specimen S-T2 is shown as a representative example as the lighter coarse aggregate contrasts well with the darker colored fine aggregate. The coverage ratios will be discussed in the following subsections.

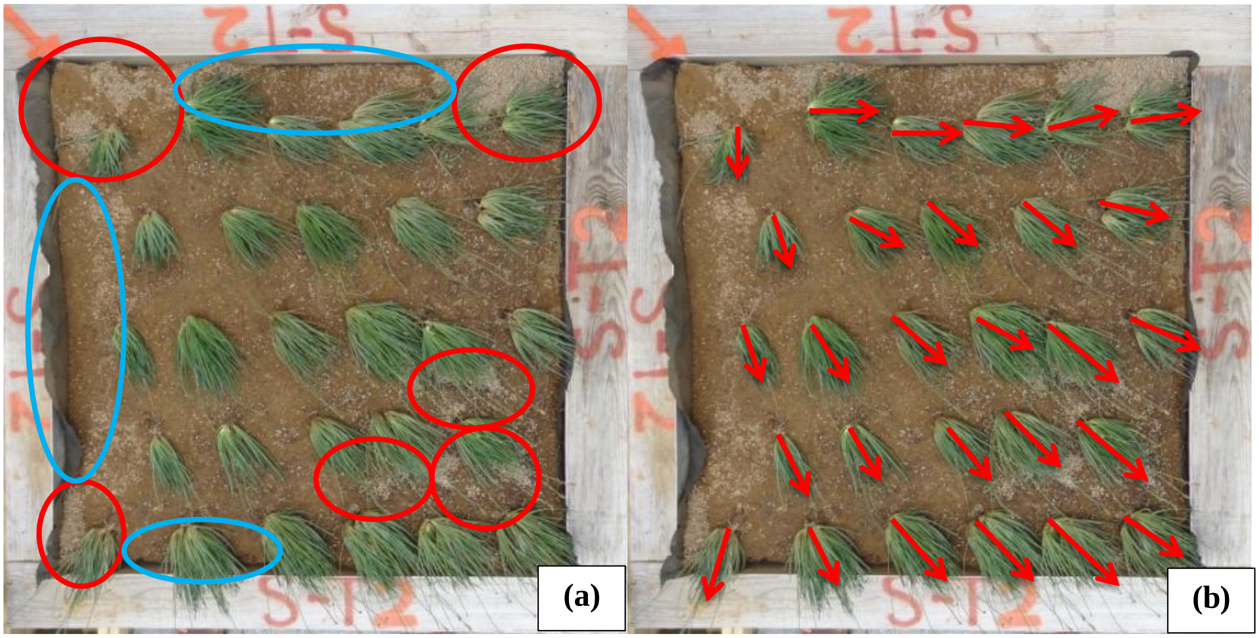


Figure 10. (a) Key areas of scour: red circles represent coarse aggregate build-up, and blue circles represent edge losses, **(b)** The general direction of the conical vortices and wind flow across the BIP system is represented by the direction in which plants bent, depicted by the red arrows

5.4.2.1.2 Sheltering effect from plants

One apparent observation made by the investigators was the sheltering effect that plants have on coarser aggregate. The short plant species resulted in very little losses of the coarse material, as was expected from their pronounced coverage ratio. Taller plants, however, also exhibited signs of sheltering. As seen above in **Figure 10 (a)**, plants that were bent over further away from the windward corner towards the leeward corner offered a sheltering effect for the coarse aggregate. This sheltering effect is more pronounced across the deck as the coverage ratio is increased, as differentiated by **Figure 11 (a) & (b)**.

Figure 11. Comparison of sheltering effect in leeward corner at the end of two different 20 minute wind tests for **(a)** S-T1: Lantana, and **(b)** S-T2: Bulbine

5.4.2.1.3 Tall vs. short

Both tall and short BIP specimens displayed very similar scour behaviors based on the post-test overhead photographs. Comparisons in coverage ratio losses between the normally saturated tests (N-S1, N-S2 vs. N-T1, N-T2) show that shorter plant species resist scour effects much more effectively than taller plants. In ten (10) minutes of testing, N-S1 and N-S2 (short specimens) lost 15% and 8% of their original coverage ratio, as compared to N-T1 and N-T2 (tall specimens) losing 31% and 19%, respectively. The authors attribute this with a larger frontal area being exposed to the wind for taller plant species, whereas shorter plants stay relatively low to the roof surface, avoiding the blunt force that causes the extreme bending. This reasoning also reinforces the presence of those conical vortices close to the edges being the only possible forces which could create the plant displacement pattern in short species. The authors also witnessed extreme aggregate blow-off when testing the Bulbine specimens due to their incredibly low coverage ratio. Coarse aggregate was nearly all blown-off for both N-T2 and N-T1.

5.4.2.1.4 Normal saturation vs. high saturation

A direct comparison between the short plant specimens will show that a correlation between increased saturation levels and increased coverage ratio reduction exists. The scour patterns are much more pronounced in the highly saturated short plant specimens in comparison to the normally saturated specimens. When comparing the tall plant specimens, however, that correlation weakens, either due to the plants offering a somewhat wider spread of coverage once bent downwards (as in the case with the Bulbine species) or that the tall species highly saturated conditions were tested a week after the normally saturated conditions, allowing for further plant growth and higher coverage ratios.

5.4.2.1.5 Extended testing time

Test trials S-T1 and S-T2 were exposed to both higher saturation levels (exposure to 55 gallons of water) and longer wind testing times to represent the worst-case scenario for BIP green roof systems. It was found that the initial 10 minutes of testing resulted in the most significant reduction in coverage ratio. The second 10 minute segment resulted in very minimal differences in coverage ratio for both S-T1 and S-T2. The authors attribute this to the taller plants' ability to stay bent and low, mimicking the behavior of short plant species. Despite this, the lack of coverage resulted in significant losses in growth media as shown in **Figure 12 (a) and (b)**.

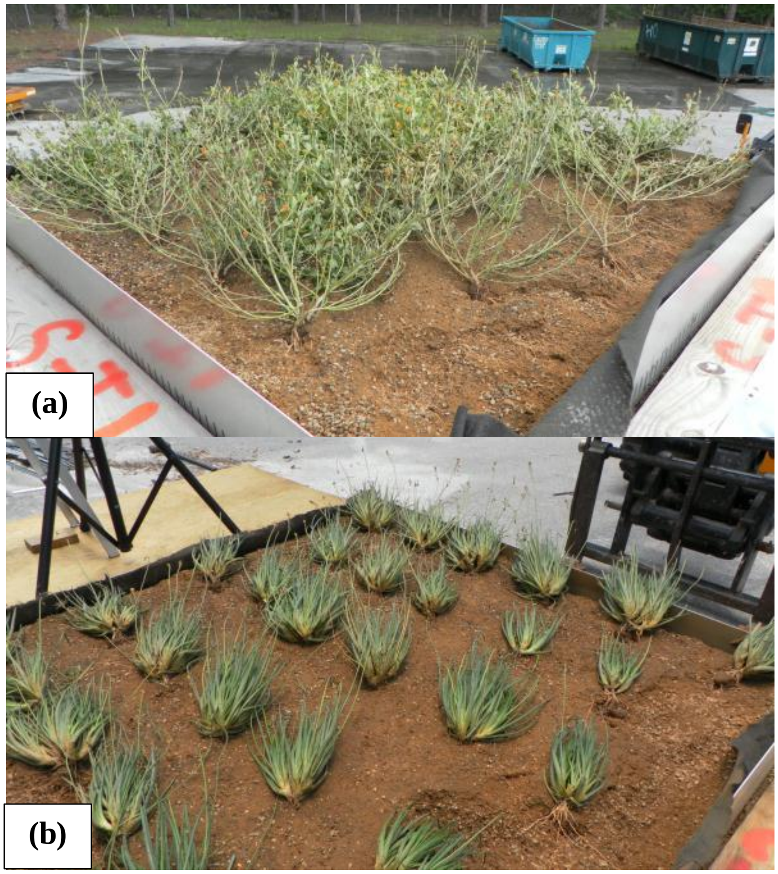


Figure 12. Significant substrate scouring in **(a)** S-T1, and **(b)** S-T2

5.4.2.2 Modular tray green roof systems

5.4.2.1.1 Problematic zones and scour direction

The modular tray green roof tests did not exhibit significant problematic zones and as distinct scour directions as the BIP green roof results. This could be due to the localized nature of the scour pattern, the significantly longer establishment period these specimens were allowed, the smaller volume of substrate that these plants were confined to grow in, or the combined effect of all three factors. Scour direction for different specimen sets varied unlike what was seen in Section 5.4.2.1.1, and the problematic zones were typically the corners and edges of the modules, as well as the leading corner module. However, these zones were highly dependent upon the orientation of each module, as well as the performance of each plant species within the module – both of which were not controlled or accounted for. **Figure 13 (a)** and **(b)** show scour patterns and zones that are closely similar to those seen in the BIP green roofs in Section 5.4.2.1.1. However in looking at specimen set T10 which utilized the same types of plants as specimen set T7 in 8 in. deep modules, the scour direction becomes more uniform and parallel with the direction of the hurricane simulator wind flow. Also, build-up of coarser aggregate seems much more apparent in specimen set T10.

Figure 13. (a) Problematic zones with blue circles representing scour and aggregate loss, and red circles representing coarse aggregate build-up; and **(b)** Scour direction determination after a 20 minute prolonged test on specimen set T7

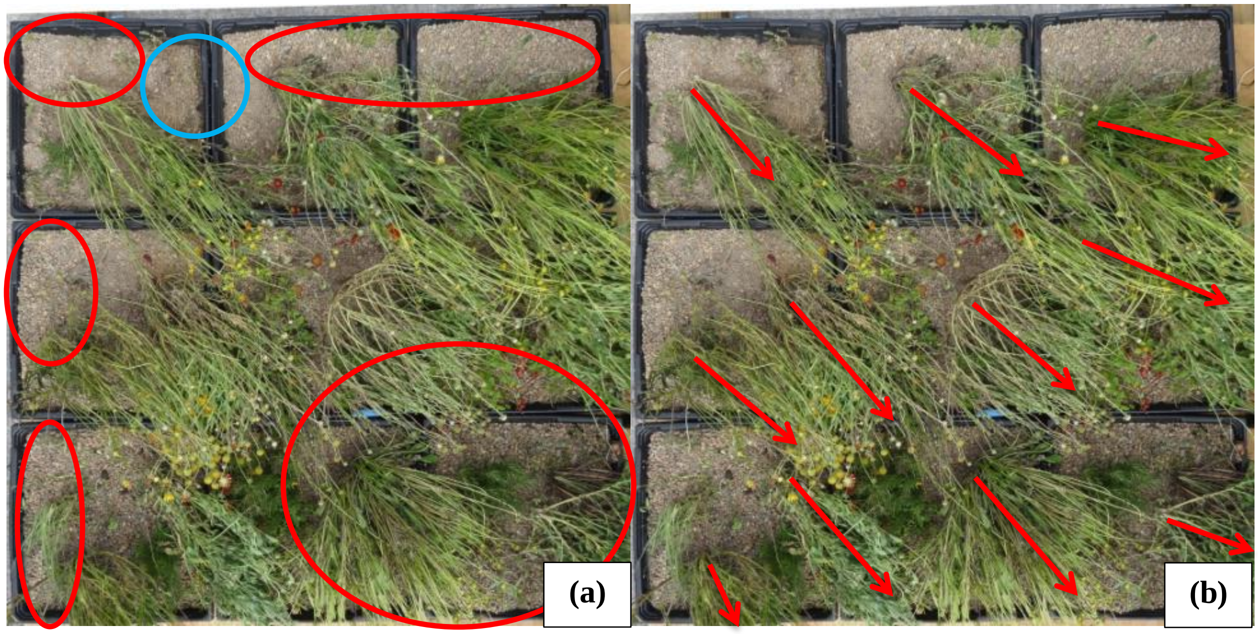


Figure 14. (a) Problematic zones with blue circles representing scour and aggregate loss, and red circles representing coarse aggregate build-up; and **(b)** Scour direction determination after a 20 minute prolonged test on specimen set T10

5.4.2.2.2 Tall vs. short

With these problematic zones identified, it would be expected for the module located in the leading corner to experience the most notable weight loss. This assumption seems to be reinforced by the post-test weight differences for the specimen sets shown above (T7 and T10). The two leading corner modules, T7-3 and T10-7, lost 20% and 13% of their original weight, respectively in comparison to notably smaller losses of other modules in their respective specimen sets. To confirm that the leading corner was indeed a problematic zone which experienced the highest losses, a comparison must be made with a specimen set of same establishment length and module depth. While the 4 inch specimen set, T7, lacked any a comparable 6 month set due to premature failure, a comparison could be made between specimen sets T10 and T11. Both specimen sets had rather similar coverage ratios from the overhead photography, but surprisingly, the leading corner module in T11, T11-6, only lost a total of 0.8% of its original weight, and had average total losses when compared to the rest of its specimen set. Therefore, the investigators confirmed with their findings in the BIP test trials that given a set establishment period, coverage ratio, and module depth, the plant height plays a vital role in determining how much losses is experienced by a green roof.

5.4.2.2.3 Sheltering effect from plants

As seen in the BIP test trials, a pronounced sheltering effect of plants on the substrate was seen for those specimen sets with high coverage ratios. This, as expected, was quite apparent in specimen sets containing short, low-lying plants. However, with the knowledge from a parallel root uplift study showing signs that the modular substrate has been locked into a single system by the intertwined root systems (**Figure 15**), media losses in the modular specimens should not be expect to be as extreme the longer the establishment period.

Figure 15. Uprooted substrate system, completely binded by roots

5.4.2.2.4 Moisture content effects

Referring to the figures in Section 5.3.1.4, moisture content effects can be seen as negligible in determining the losses.

5.4.3 Failure modes

Observed in both BIP and modular green roof tests, the predominant plant failure mode observed was root lodging. Stem lodging rarely occurred, and was only witnessed in taller plant species. Complete failure, however, did occur within two (2) of the modular tray specimen sets.

5.4.3.1 Built-in-place green roof systems

Only a few instances of plant uprooting were observed during the BIP test trials, as summarized by **Table 11** in Section 5.3.2. That said, the Lantana (N-T1 and S-T1) portrayed the most potential to become windborne debris in a windstorm event with complete plant failures observed in both test trials.

Root lodging was the predominant failure mode observed in the BIP tests, appearing in all BIP test trials. Root lodging was the instance when the root ball or system was exposed due to significant scouring and/or the overturning of a plant. Stem lodging occurred, and was rarely documented. **Figure 16** shows the common root lodging and stem lodging case in a Lantana specimen. Both types of lodging are seen to occur more commonly in taller plants than shorter plants, as expected by the investigators.

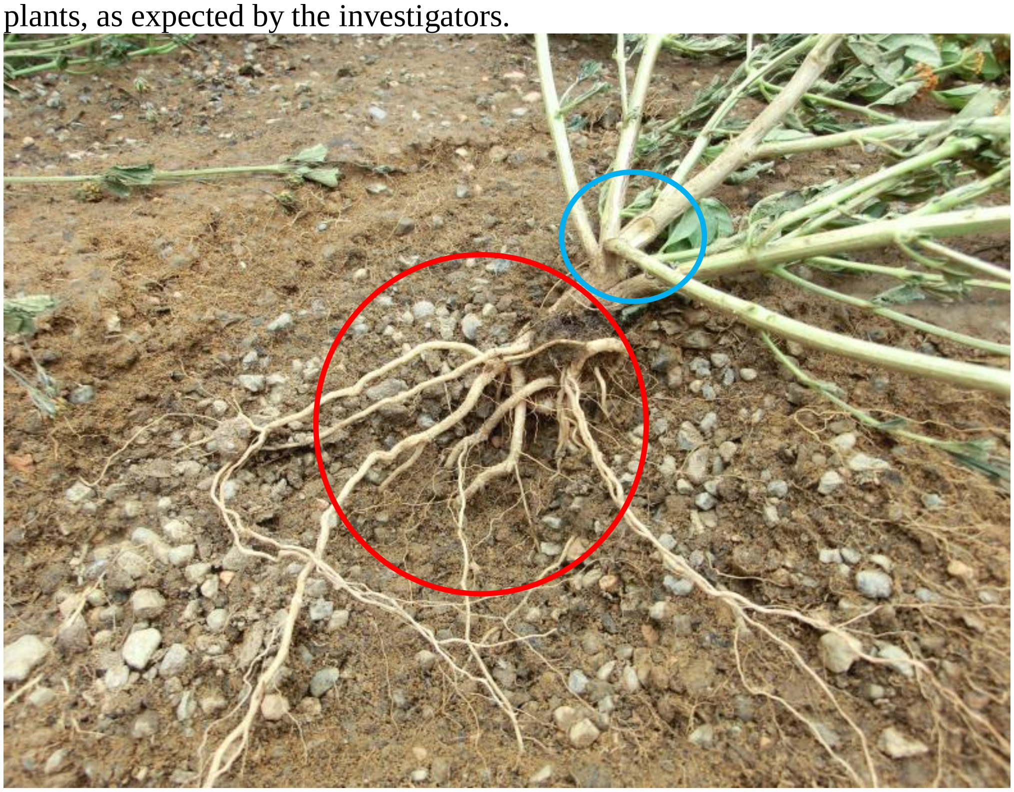


Figure 16. Root lodging shown in red circle and stem lodging shown in the blue circle

5.4.3.2 Modular green roof systems

The first failure mode that should be addressed is the complete uplift of the modular tray system. The investigators determined that failure mechanism resulted from a combination of high uplift forces caused by the conical vortices, close proximity of the modules to the leading edges, light weight of the extensive green roof modules (≈13 psf), and the lack of a parapet. Once the parapet wall was removed, very little remained to adequately prevent the wind from blowing off the modules. The parapet wall, in Phase 1, was able to block direct wind flow from directly striking as well as flowing underneath the windward row of modules to initiate uplift. A similar vertical displacement, or "fluttering," seen in the windward corner module of specimen set T3 and T8 could be seen in test trial 4" T1.1 in Phase 1. When flow reversal occurred, high wind forces were present on the back row of modules, and scoured much of the unplanted module's growth media off. This eventually led to a fluttering effect that worsened as more material was lost. Failure in T3 exposed the high vulnerability of a system of 4 in. green roof modules set to a worst-case scenario.

The modular tray specimens experienced both root and stem lodging. However, unlike the BIP trays, these failure modes were highly localized to the individual module performance, rather than widespread, uniform failures. Like the BIP green roofs, taller plants typically had a higher risk of experiencing root and/or stem lodging. It should be noted that the Gaillardia species found in specimen sets T7 and T10 are considered *top-heavy*, meaning that the species typically grows a heavy bud at the end of a long, slender stem to easily collapse and propagate. Therefore, stem lodging is expected, but complete breakage is difficult due to the resilient nature of the stem. **Figure 17 (a)** shows typical root lodging, whereas stem lodging in modular tray green roofs is shown by **Figure 17 (b)**.

Figure 17. (a) Root lodging of Salvia ; **(b)** Stem lodging of a Gaillardia

6. PLANT PERFORMANCE

While the bulk of the project assigned called for a wind performance study, the investigators and the FBC were also interested the specific plant species that would thrive in the state of Florida. Quantification of plants' performance during wind testing is highly difficult due to the large amount of variability in the biology of plants (stem size, roots, etc.). While several of the plant structure studies reviewed created models to allow for manageable control over those variations, the investigators of this report were more curious to see the failure mechanism of plants in their natural state. This section will review the plant selection process that the authors undertook, as well as summarize the proposed uproot testing of green roof plants.

6.1 Overview

The planting media of a green roof assembly is an aggregate media with limited organic additives that removes water quickly from the roof. While this is useful to reduce the load on the roof, with it goes the sustenance that is needed by plants. Green roofs are therefore a balancing act.

Designing green roofs in Florida's hot, humid climate (USDA Zones 8, 9 and 10) can be extreme with summer surface temperatures of conventional roofs reaching more than 145° F (Wanielista, et al., 2008), and green roof aggregate media reaching 165° F. Further, there is little cooling relief through the night. Consequently, green roofs in Florida must consider:

- harsh conditions of extreme heat and drought while
- plant selections that can thrive in the ever-present humidity and seasonally heavy rainfall

In order to design green roof wind uplift test protocols for the Florida Building Commission, there are several considerations:

1. Identify the most common roof configurations in Florida
2. Identify the most common green roof assemblies in Florida
3. Select plants that are most likely to be successful in Florida
4. Determine the parameters of plant form and planting condition in order to design the research approach to measure wind uplift

6.2 Plant selection

The selection of plants for use in uplift tests were determined by identifying plants that:

- Are commonly used in green roof applications in Florida
- Have been successful at the University of Florida's green roof (2,600 ft² [241.5 m²], installed in 2007), or in UF field trials
- Represent a variety of species, forms and performance characteristics in wind uplift

This list includes 14 species that would represent a variety of plants and wind resistance characteristics needed for uplift testing including plant form (upright vs. spreading), leaf area (small and large), stem strength (woody vs. succulent), and root characteristics (dense vs. limited). Further, the list represents a variety of native plants, hardy ornamentals, and adapted succulents that are proven in Florida applications. Each has certain useful characteristics for green roof applications including attractive color; resistance to heat and wet conditions; ability to store water for use in dry periods; and moderate to fast growth. **Table 14** displays the list of plants for wind uplift trials in both Phase 1 and Phase 2. As mentioned above, they were selected to represent diverse characteristics that represent a range of plant morphology and/or to achieve wind uplift variables. The list should not be interpreted as a list of "best plants."

Table 14. Plant list*

Phase 1			
	Botanical name	**Common name**	**Size; Stem characteristics**
A	*Aptenia cordiflora*	Baby Sun Rose	Short, succulent
B	*Delosperma cooperi*	Ice Plant	Short, succulent
C	*Dianthus gratianopolitanus*	Dianthus	Short
D	*Lantana montevidensis*	Trailing Lantana	Tall, woody
E	*Salvia rutilans*	Pineapple Sage	Tall, woody
F	*Sedum rupestre 'Angelina'*	Angelina Sedum	Short, succulent
Phase 2			
	Botanical name	**Common name**	**Size; Stem characteristics**
G	*Sedum rupestre*	Lemon Coral	Short, succulent
H	*Delosperma nubigenum*	Yellow Ice Plant	Short, succulent
I	*Rosemarinus officianalis*	Rosemary	Short, woody
J	*Gaillardia aristata*	Blanketflower	Tall
K	*Coreopsis lanceolata*	Sunray	Tall
L	*Bulbine frutescens*	Stalked Bulbine	Tall
M	*Lantaa camara*	Yellow Bush Lantana	Tall, woody
N	*Portulaca grandiflora*	Rose Moss	Short, succulent

* Short plants are 12" or less in height; tall plants are 14"-30") in height; woody plants have rigid stems; succulent plants have soft stems and foliage and store water in their foliage and stems.

6.3 Uproot testing

As part of the continuing green roof performance studies at the UF, a test method of determining individual plant resistance to uproot forces is currently being explored. The first phase of green roof performance tests studied the performance of six-month established green roof modules on top of a flat roof structure exposed to 20 to 120 mph wind speeds. From this testing it was determined that further research was needed understand how a plants root system stabilizes green roof media during periods of high winds.

The qualitative results produced from Phase 1 of UF's wind testing, in addition to the outcomes of previous studies suggest plants, are attributed to providing sufficient soil/media stability and anchorage through their root systems. The species of plants utilized for the uproot testing and in the green roof wind uplift study were selected based on availability, survivability, growth rates, and also potential for wind resistance within the North Central Florida Region. The results of the initial wind testing conducted in summer 2011 demonstrated the need to obtain additional uplift resistance dataset between plant species to provide further beneficial guidance towards plant selection in Florida. The purpose of this section is to provide a background of three existing root uplift resistance studies and their testing procedures, as well as to explain the methods, materials, and test matrix of the current of uproot tests being conducted at UF.

6.3.1 Review of previous root uplift studies' test methods

6.3.1.1 2010 – Mickovski, S.B. et al. – Resistance of simple plant root systems to uplift loads

This study explored the axial uplift resistance of a single, vertical tap root. The authors first measured the axial stiffness against the root diameter of three month old willow roots to obtain a range for the mechanical properties of the root system. Then, to normalize for biological variability factors (root size, branching, etc.) that would be present in real root systems, the authors fabricated model roots made of two different materials based on the previous measurements, Viton O-ring rubber and Linden wood rods. This allowed for the direct comparison of the root-soil interaction without uncertainties. The authors acknowledged that this simplification is not representative of real root systems which are far more complex and variable in terms of growth and dimensions.

The study validated the material of the roots via interface direct shear tests and rigid root pullout tests. After preparation of the sand was completed, the authors clamped the exposed portion of the root model, attached to the load cell of the universal testing machine (UTM) (INSTRON 5540), and pulled out of the soil at a constant rate of 1 mm/min. By varying the root material and sand saturation (dry or saturated), the authors were able to measure the loads and displacements on each root testing scenario. The same test procedure was then followed for root samples obtained from two 3 year old willow trees having similar geometry as the model roots.

6.3.1.2 2007 – Hamza, O. et al. – Mechanics of root-pullout from soil: A novel image and stress analysis procedure

The authors conducted a study similar to that by Mickovski et al. in 2010. Instead of focusing on a single, vertical root tap, the authors utilized four different model root systems made of Viton rubber. Again, model root systems were pursued to allow for control over variations in plant biology present in nature. Two of the root models were similar to Mickovski's study, consisting of single vertical root taps, with the two models differing in root length. The third and fourth root models provided a somewhat more representative system as seen in real plants. The former consisted of a single root tap with an additional two branches, while the latter has an additional four branches. Comparisons were made between root uplift tests performed on the model root systems and planted seedlings (Pea and Maize plants).

Like what was seen in Mickovski et al.'s study in 2010, the authors utilized a UTM (INSTRON 5540) to measure the load and displacement of the root systems tested. The displacement rate was set at 0.05 mm/s (3 mm/min), which was a bit faster than Mickovski et al.'s displacement rate. The authors clamped the free end of the root to the displacing end of the UTM using screwthread grips with hard rubber surfaces. The container of soil was fixed to the UTM's base. A sequence of photos was taken and a Particle Image Velocimetry (PIV) was performed to detect the movement of pixels between images. This was only possible because the container was made of clear Perspex surfaces, enabling the authors to see the root system under the soil.

6.3.1.3 2002 – Baily, P.H.J. et al. – The role of root system architecture and root hairs in promoting anchorage against uprooting forces in Allium cepa and root mutants of Arabidopsis thaliana

This study addressed the role of multiple roots, the impact of laterals and the contribution of root hairs to anchorage. To do so, the authors utilized two species of plants, *Allium cepa* (onion) and *Arabidopsis thaliana* (thale cress). The former was chosen to represent a root system that was relatively thick, unbranched and uniform in width while the latter produced root systems that were "wild" and branched out with root hairs. The authors sought to distinguish whether a deeper, more uniform root system (from the onion species) would increase anchorage or not. This would provide insight on whether lateral growth was important or not.

The authors grew these plants within a controlled environment, noting how often the plants were watered, and the amount of light provided. Before testing with a UTM, the authors watered the plots with tapwater until saturated, and allowed to drain between 30 to 90 minutes. The plants were all clamped with a corrugated metal grip lined with thin pieces of rubber. If the stem broke during testing, the results were discarded.

Uprooting tests were performed for both the onion and thale cress plants. The latter were pulled up at 100 mm/min (200 mm/min for a different harvest, but did not yield differing results) while the former was pulled up at 500 mm/min.

In determining individual root strengths for the onion, the root nearest the stem was cut. The ends of this root were then super-glued between steel plates, and allowed to dry for approximately 30 minutes. The central non-glue section was then tested by attaching the steel-plated ends on the UTM and displacing at a 20 mm/min rate until failure.

6.3.2 Testing parameters

The following list of parameters were acknowledged to affect the results obtained from the uproot tests. The parameters underlined will be accounted for:

- Establishment length – 6 month (younger root system age and moderate root dispersal) vs. 12 month (mature root system and dispersal)
- Growth media depth – 4" vs. 8". (greater media depth encourages greater plant and root vigor)
- Growth media moisture content – Moisture will enhance root pull resistance. Therefore uproot tests will be performed as normally saturated or wet.
- Plant species habit/shape – Taller plants are subject to greater wind uplift vs. shorter plants; woody plant stems are typically stronger than soft, succulent stems
- Whether exposed to wind testing or not
- Time between uproot test and simulator test
- Location on flat roof during simulator test (important to keep 12 month modules in same locations for Phase 2 studies)

- Density of plants in test cell – Greater plant coverage enhances protection against wind stress and will lessen any effects during simulator testing that may lessen pull out resistance
- <u>Root type and dimensions (length, spread, depth)</u> – Plants' root systems dimensions, dispersal and strength vary by species.

6.3.3 Uproot test matrix and selection procedure

Due to the modules being planted with either 4 to 6 different herbaceous, dicot plant species, similitude does not exist between these test results and those from the cited studies. Therefore, with 100 planted modules, it is suggested that from the current stock of plant species (to be provided), a standard selection is made, and each module be uprooted only once. Reasoning behind this would be due to root establishment of each plant species essentially affecting each other. The plant selection in each group below was chosen to represent one (1) succulent and one (1) herbaceous species.

Table 15. Plant species uproot test matrix

		Establishment Time					
		12 months	#	**6 months**	#	**1.5 months**	#
Media Depth	**4"**	A B1	3 3	C D	3 3	-	-
	8"	A B1	3 3	C D	3 3	-	-
	6"	-	-	-	-	A B2	3 3

A – *Aptenia cordiflora* B2 – *Lantana camara* C – *Delosperma cooperi*
B1 – *Lantana montevidensis* D – *Gaillardia aristata*

6.3.4 Plant Uproot Device (PUD)

For the testing, a Plant Uproot Device (PUD) was designed and constructed on-site at the Powell Laboratory, located at the University of Florida Eastside Campus. The device consisted of: a custom designed, foam and rubber insert clamp, S-shaped hanging load cell with 200-lb capacity, 1/16" steel rope cable, and a 6" linear electric actuator, all connected to a data acquisition system. Utilizing two, 4" U-bolts, the actuator was vertically mounted to a 2"x8"x8' piece of pressure treated lumber placed on-end horizontally between two, 41" tripod supports (**Figure 18 (a) & (b)**). Testing was performed by attaching the foam and rubber insert clamp to the base of the selected plants and retracting the actuator in an upwards motion until the plant's root system became detached from the green roof media (**Figure 19**). Because the PUD was a combination of two separate pieces of equipment (load cell and linear actuator), a Labview program was created to record the time history of the linear actuator's displacement and the load cell's force reading at a 50 Hz frequency. These records are printed and saved as output text files defined by the user.

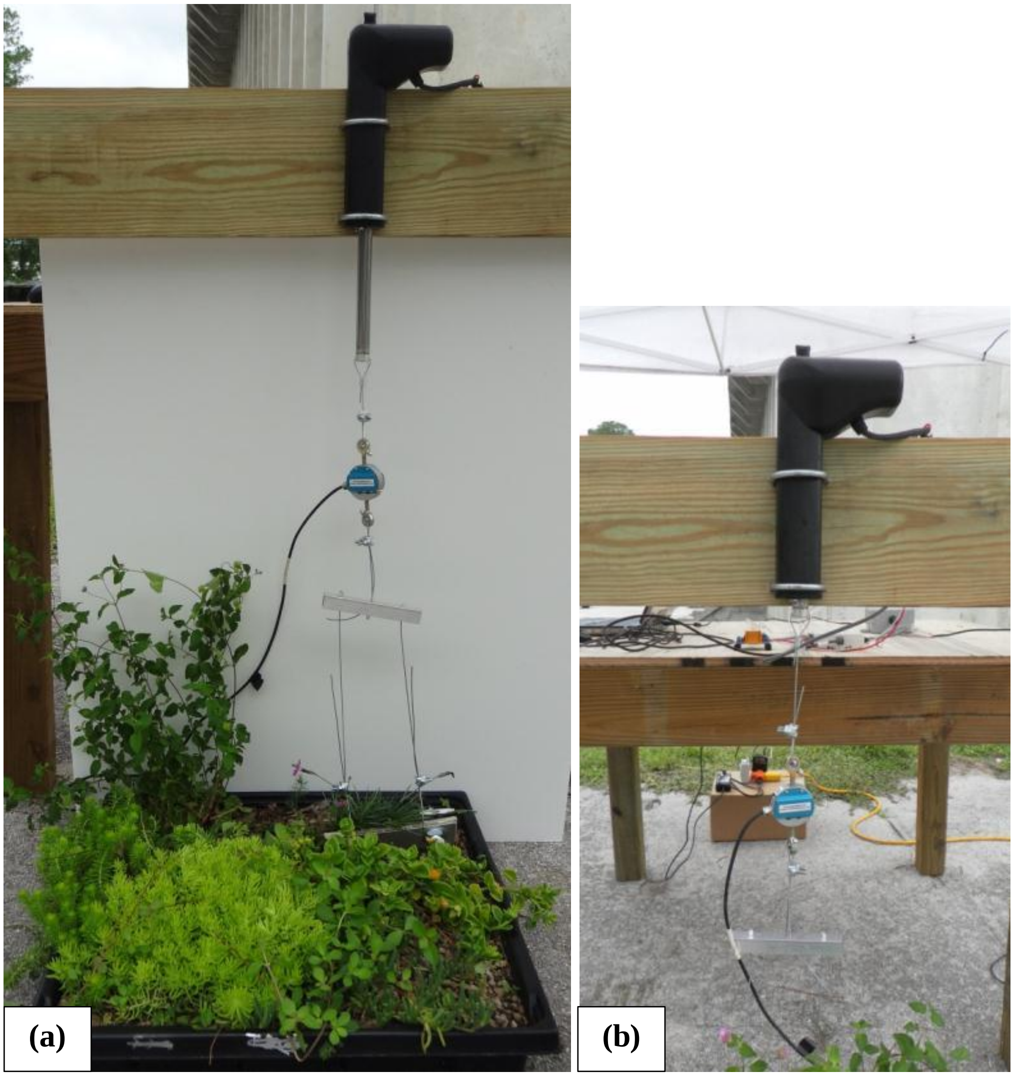


Figure 18. (a) Plant uproot device (PUD); **(b)** Actuator and load cell attachment shown


Figure 19. Foam and rubber insert clamp attached to different plants that have been uprooted

Figure 20. Data recording equipment

6.4 Root documentation

Immediately following plant uproot testing, the root systems will be cleaned off and placed on a clean, white gridded board (**Figure 21**). The goal is to photo-document the growth habit of their root systems. Since the wind uplift testing involves a variety of plant species, different amounts of time grown in situ, and different media depths, it is expected that there will be variations in the potential success or failure of plant uprooting. Media depth alone has been observed as a factor in the better growth rate of plants in the 8” versus 4” tray depths. The purpose of this photo-analysis is to determine the relationship (if any) between root spread, root uplift force, and wind-induced failure of a plant. Further, having plants grown in situ for 2, 6 and 12 months represent 3 different phases in maturity, extent and strength of root systems, and each contributes differently to the securing of the plant in wind uplift as well as the uptake of nutrients.

Figure 21. Lantana placed on gridded board with beginning of root system starting at depth = 0 in.

REFERENCES

[1] Alfredo, K., Montalto, F., and Goldstein, A. (2010). "Observed and modeled performances of prototype green roof test plots subjected to simulated low- and high-intensity precipitations in a laboratory experiment." *Journal of Hydrologic Engineering*, 15(6), 444-457.

[2] DeNardo, J. C., Jarrett, A. R., Manbeck, H. B., Beattie, D. J., and Berghage, R. D. "Stormwater Detention and Retention Abilities of Green Roofs." *Proc., World Water and Environmental Resources Congress 2003, June 23, 2003 - June 26, 2003*, American Society of Civil Engineers, 1639-1645.

[3] Getter, K. L., Rowe, D. B., and Andresen, J. A. (2007). "Quantifying the effect of slope on extensive green roof stormwater retention." *Ecological Engineering*, 31(4), 225-231.

[4] Nagase, A., and Dunnett, N. (2012). "Amount of water runoff from different vegetation types on extensive green roofs: Effects of plant species, diversity and plant structure." *Landscape and Urban Planning*, 104(3-4), 356-363.

[5] Long, B., Clark, S. E., Baker, K. H., and Berghage, R. "Selecting a green roof medium for water quality benefits." *Proc., 2007 World Environmental and Water Resources Congress: Restoring Our Natural Habitat, May 15, 2007 - May 19, 2007*, American Society of Civil Engineers (ASCE), Environ. Water Resour. Inst. (EWRI) Am. Soc. Civ. Eng. (ASCE).

[6] Long, B. V., Clark, S. E., Berghage, R., and Baker, K. "Green roofs - A BMP for urban stormwater quality?" *Proc., World Environmental and Water Resources Congress 2008: Ahupua'a, May 12, 2008 - May 16, 2008*, American Society of Civil Engineers, Environmental and Water Resources Institute of ASCE.

[7] Long, B., Clark, S. E., Baker, K. H., and Berghage, R. "Selecting a green roof media to minimize pollutant loadings in roof runoff." *Proc., 2nd National Low Impact Development Conference 2007: New and Continuing Applications, March 12, 2007 - March 14, 2007*, American Society of Civil Engineers, 260-274.

[8] Teemusk, A., and Mander, U. (2010). "Temperature regime of planted roofs compared with conventional roofing systems." *Ecological Engineering*, 36(1), 91-95.

[9] Alexandri, E., and Jones, P. (2008). "Temperature decreases in an urban canyon due to green walls and green roofs in diverse climates." *Building and Environment*, 43(4), 480-493.

[10] Susca, T., Gaffin, S. R., and Dell'Osso, G. R. (2011). "Positive effects of vegetation: Urban heat island and green roofs." *Environmental Pollution*, 159(8-9), 2119-2126.

[11] Figueroa, M., and Schiler, M. "Green roof performance: Passive design implications in Los Angeles, California." *Proc., 26th International Conference on Passive and Low Energy Architecture: Architecture Energy and the Occupant's Perspective, PLEA 2009, June 22, 2009 - June 24, 2009*, Les Presses de l'Universite Laval.

[12] La Roche, P. "Green cooling: Combining vegetated roofs with night ventilation." *Proc., ASME International Solar Energy Conference - Solar Engineering 2006, July 9, 2006 - July 13, 2006*, American Society of Mechanical Engineers, ASME, SOLAR ENERGY DIVISION.

[13] La Roche, P. "Low cost green roofs for cooling: Experimental series in a hot and dry climate." *Proc., 26th International Conference on Passive and Low Energy Architecture: Architecture Energy and the Occupant's Perspective, PLEA 2009, June 22, 2009 - June 24, 2009*, Les Presses de l'Universite Laval.

[14] Sonne, J. (2006). "Evaluating green roof energy performance." *ASHRAE Journal*, 48(2), 59-61.

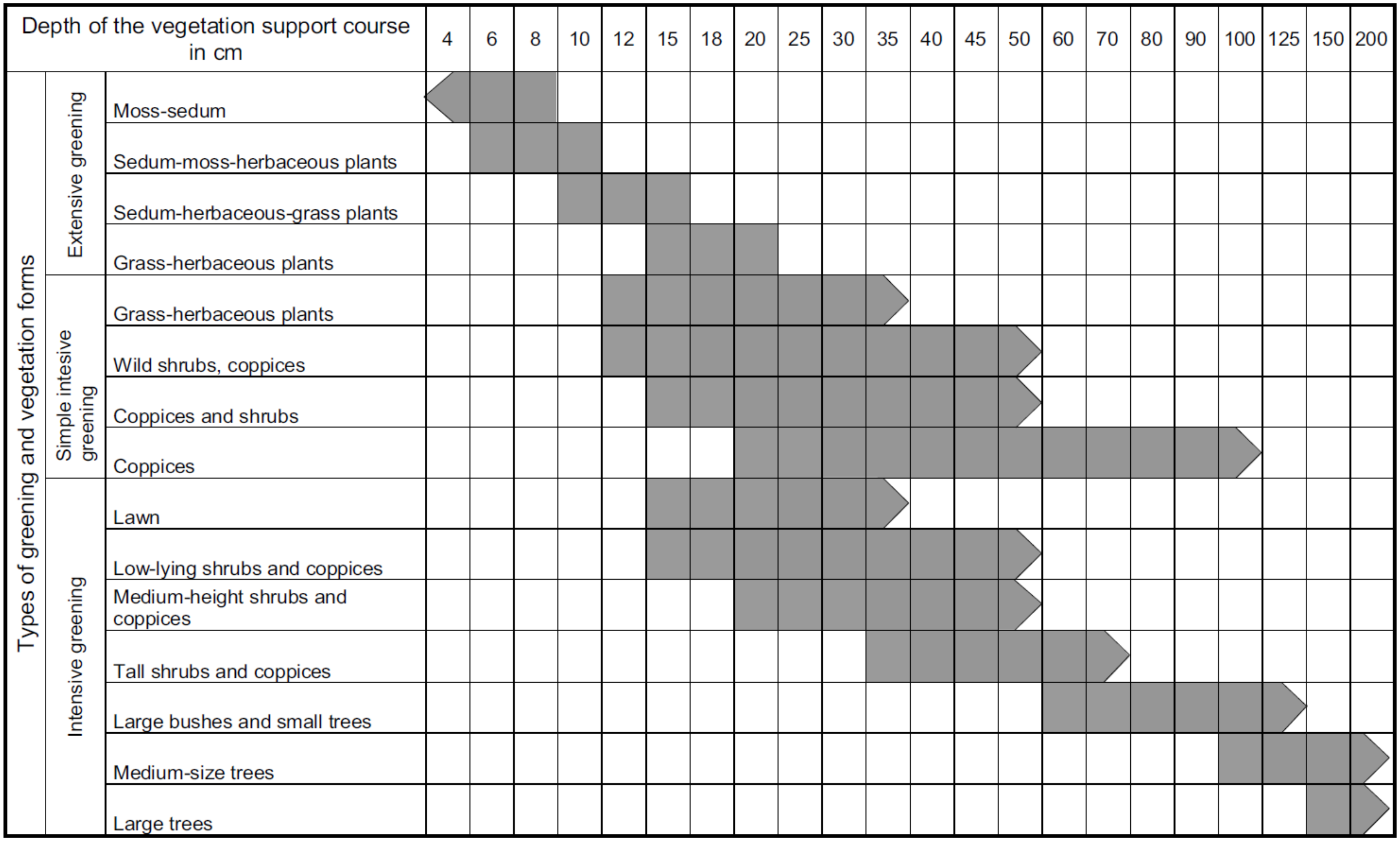
[15] Castleton, H. F., Stovin, V., Beck, S. B. M., and Davison, J. B. (2010). "Green roofs; Building energy savings and the potential for retrofit." *Energy and Buildings*, 42(10), 1582-1591.
[16] Li, J.-F., Wai, O. W. H., Li, Y. S., Zhan, J.-M., Ho, Y. A., Li, J., and Lam, E. (2010). "Effect of green roof on ambient CO2 concentration." *Building and Environment*, 45(12), 2644-2651.
[17] Yang, J., Yu, Q., and Gong, P. (2008). "Quantifying air pollution removal by green roofs in Chicago." *Atmospheric Environment*, 42(31), 7266-7273.
[18] Connelly, M., and Hodgson, M. (2008). "Sound transmission loss of extensive green roofs - Field test results." *Canadian Acoustics - Acoustique Canadienne*, 36(3), 74-75.
[19] Van Renterghem, T., and Botteldooren, D. (2008). "Numerical evaluation of sound propagating over green roofs." *Journal of Sound and Vibration*, 317(3-5), 781-799.
[20] Van Renterghem, T., and Botteldooren, D. (2009). "Reducing the acoustical facade load from road traffic with green roofs." *Building and Environment*, 44(5), 1081-1087.
[21] Van Renterghem, T., and Botteldooren, D. (2011). "In-situ measurements of sound propagating over extensive green roofs." *Building and Environment*, 46(3), 729-738.
[22] Yang, H. S., Kang, J., and Choi, M. S. (2012). "Acoustic effects of green roof systems on a low-profiled structure at street level." *Building and Environment*, 50, 44-55.
[23] Prevatt, D. O., Masters, F. J., and Vo, T. D. (2011). "State of Knowledge of Green Roofs in State of Florida." University of Florida, Gainesville, FL, USa, 26.
[24] Kramer, C., Gerhardt, H. J., and Scherer, S. (1978). "WIND PRESSURE ON BLOCK-TYPE BUILDINGS." *Journal of industrial aerodynamics*, 4(3-4), 229-242.
[25] Lythe, G., and Surry, D. (1982). "WIND LOADING OF FLAT ROOFS WITH AND WITHOUT PARAPETS." *Journal of Wind Engineering and Industrial Aerodynamics*, 11(1-3), 75-94.
[26] Stathopoulos, T., Baskaran, A., and Goh, P. A. (1990). "Full-scale measurements of wind pressures on flat roof corners." *Journal of Wind Engineering and Industrial Aerodynamics*, 36, Part 2(0), 1063-1072.
[27] Surry, D. (1991). "Pressure measurements on the Texas tech building: Wind tunnel measurements and comparisons with full scale." *Journal of Wind Engineering and Industrial Aerodynamics*, 38(2–3), 235-247.
[28] Bienkiewicz, B., and Sun, Y. (1992). "Local wind loading on the roof of a low-rise building." *Journal of Wind Engineering and Industrial Aerodynamics*, 45(1), 11-24.
[29] Baskaran, B. A., and Savage, M. G. (2003). "Wind pressure measurements on full scale flat roofs." *Interface*, 21(4), 5.
[30] Blessing, C., Chowdhury, A. G., Lin, J., and Huang, P. (2009). "Full-scale validation of vortex suppression techniques for mitigation of roof uplift." *Engineering Structures*, 31(12), 2936-2946.
[31] Kind, R. J. (1986). "Worst suctions near edges of flat rooftops on low-rise buildings." *Journal of Wind Engineering and Industrial Aerodynamics*, 25(1), 31-47.
[32] Kopp, G. A., Surry, D., and Mans, C. (2005). "Wind effects of parapets on low buildings: Part 1. Basic aerodynamics and local loads." *Journal of Wind Engineering and Industrial Aerodynamics*, 93(11), 817-841.
[33] Sockel, H., and Taucher, R. (1981). "The influence of a parapet on local pressure fluctuations." *Journal of Wind Engineering and Industrial Aerodynamics*, 8(1–2), 31-38.
[34] Baskaran, A., and Stathopoulos, T. (1988). "Roof corner wind loads and parapet configurations." *Journal of Wind Engineering and Industrial Aerodynamics*, 29 pt 2(1-3), 79-88.

[35] Stathopoulos, T., and Baskaran, A. (1988). "Turbulent wind loading of roofs with parapet configurations." *Canadian journal of civil engineering*, 15(4), 570-578.
[36] Kareem, A., and Lu, P. C. (1992). "Pressure fluctuations on flat roofs with parapets." *Journal of Wind Engineering and Industrial Aerodynamics*, 43(1–3), 1775-1786.
[37] Kopp, G. A., Mans, C., and Surry, D. (2005). "Wind effects of parapets on low buildings: Part 2. Structural loads." *Journal of Wind Engineering and Industrial Aerodynamics*, 93(11), 843-855.
[38] Stathopoulos, T., Marathe, R., and Wu, H. (1999). "Mean wind pressures on flat roof corners affected by parapets: field and wind tunnel studies." *Engineering Structures*, 21(7), 629-638.
[39] Pindado, S., and Meseguer, J. (2003). "Wind tunnel study on the influence of different parapets on the roof pressure distribution of low-rise buildings." *Journal of Wind Engineering and Industrial Aerodynamics*, 91(9), 1133-1139.
[40] Suaris, W., and Irwin, P. (2010). "Effect of roof-edge parapets on mitigating extreme roof suctions." *Journal of Wind Engineering and Industrial Aerodynamics*, 98(10–11), 483-491.
[41] Kramer, C., Gerhardt, H. J., and Kuster, H. W. (1979). "On the wind-loading mechanism of roofing elements." *Journal of Wind Engineering and Industrial Aerodynamics*, 4(3–4), 415-427.
[42] Kind, R. J., and Wardlaw, R. L. (1982). "Failure mechanisms of loose-laid roof-insulation systems." *Journal of Wind Engineering and Industrial Aerodynamics*, 9(3), 325-341.
[43] Kramer, C., and Gerhardt, H. J. (1983). "Wind loads on permeable roofing systems." *Journal of Wind Engineering and Industrial Aerodynamics*, 13(1–3), 347-358.
[44] Bienkiewicz, B., and Meroney, R. N. (1988). "Wind Effects on Roof Ballast Pavers." *Journal of Structural Engineering*, 114(6), 1250-1267.
[45] Wacker, J., Friedrich, R., Plate, E. J., and Bergdolt, U. (1991). "Fluctuating wind load on cladding elements and roof pavers." *Journal of Wind Engineering and Industrial Aerodynamics*, 38(2-3), 405-418.
[46] Bienkiewicz, B., and Sun, Y. (1992). "Wind-tunnel study of wind loading on loose-laid roofing systems." *Journal of Wind Engineering and Industrial Aerodynamics*, 43(pt 3), 1817-1828.
[47] Bienkiewicz, B., and Sun, Y. (1997). "Wind loading and resistance of loose-laid roof paver systems." *Journal of Wind Engineering and Industrial Aerodynamics*, 72(1-3), 401-410.
[48] Kind, R. J. (1974). "Estimation of critical wind speeds for scouring of gravel or crushed stone on rooftops."Ottawa, Canada, 29.
[49] Kind, R. J. (1974). "Wind tunnel tests on some building models to measure wind speeds at which gravel is blown off rooftops." National Research Council Canada, Ottawa, Canada, 32.
[50] Kind, R. J., and Wardlaw, R. L. (1976). "Design of rooftops against gravel blow-off."Canada, 34.
[51] Masters, F., and Gurley, K. (2008). "Performance of Embedded Gravel Roof Systems in Extreme Wind Loading." University of Florida, Gainesville, FL, 22.
[52] Wills, J. A. B., Lee, B. E., and Wyatt, T. A. (2002). "A model of wind-borne debris damage." *Journal of Wind Engineering and Industrial Aerodynamics*, 90, 11.
[53] (ANSI), A. N. S. I., and (SPRI), S. P. R. I. (2008). "ANSI/SPRI RP-4 2008 Wind Design Standard For Ballasted Single-ply Roofing Systems." SPRI, Waltham, MA, 33.
[54] Lancaster, N., and Baas, A. (1998). "Influence of vegetation cover on sand transport by wind: field studies at Owens Lake, California." *Earth Surface Processes and Landforms*, 23(1), 69-82.

[55] Kim, D. S., Cho, G. H., and White, B. R. (2000). "A Wind-tunnel Study of Atmospheric Boundary-Layer Flow over Vegetated Surfaces to Suppress PM10 Emission on Owens (dry) Lake." *Boundary-Layer Meteorology*, 97(2), 309-329.
[56] Burri, K., Gromke, C., Lehning, M., and Graf, F. (2011). "Aeolian sediment transport over vegetation canopies: A wind tunnel study with live plants." *Aeolian Research*, 3(2), 205-213.
[57] Walter, B., Gromke, C., Leonard, K., Clifton, A., and Lehning, M. (2011). "Measurements of surface shear stress distribution in live plant canopies." *13th International Conference on Wind Engineering*Amsterdam, The Netherlands, 8.
[58] Dong, Z., Gao, S., and Fryrear, D. W. (2001). "Drag coefficients, roughness length and zero-plane displacement height as disturbed by artificial standing vegetation." *Journal of Arid Environments*, 49(3), 485-505.
[59] Sterling, M., Baker, C. J., Berry, P. M., and Wade, A. (2003). "An experimental investigation of the lodging of wheat." *Agricultural and Forest Meteorology*, 119(3–4), 149-165.
[60] Duan, J. G., Barkdoll, B., and French, R. (2006). "Lodging velocity for an emergent aquatic plant in open channels." *Journal of Hydraulic Engineering*, 132(10), 1015-1020.
[61] Jin, X., Fourcaud, T., Li, B., and Guo, Y. "Towards modeling and analyzing stem lodging for two contrasting rice cultivars." *Proc., 3rd International Symposium on Plant Growth Modeling, Simulation, Visualization and Applications, PMA09, November 9, 2009 - November 13, 2009*, IEEE Computer Society, 253-260.
[62] Berry, P. M., Sterling, M., and Mooney, S. J. (2006). "Development of a Model of Lodging for Barley." *Journal of Agronomy and Crop Science*, 192(2), 151-158.
[63] Berry, P. M., Sterling, M., Baker, C. J., Spink, J., and Sparkes, D. L. (2003). "A calibrated model of wheat lodging compared with field measurements." *Agricultural and Forest Meteorology*, 119(3–4), 167-180.
[64] Sposaro, M. M., Chimenti, C. A., and Hall, A. J. (2008). "Root lodging in sunflower. Variations in anchorage strength across genotypes, soil types, crop population densities and crop developmental stages." *Field Crops Research*, 106(2), 179-186.
[65] Ennos, A. R. (1989). "The Mechanics of Anchorage in Seedlings of Sunflower, Helianthus annuus L." *New Phytologist*, 113(2), 185-192.
[66] Goodman, A. M., and Ennos, A. R. (1999). "The Effects of Soil Bulk Density on the Morphology and Anchorage Mechanics of the Root Systems of Sunflower and Maize." *Annals of Botany*, 83(3), 293-302.
[67] Bailey, P. H. J., Currey, J. D., and Fitter, A. H. (2002). "The role of root system architecture and root hairs in promoting anchorage against uprooting forces in Allium cepa and root mutants of Arabidopsis thaliana." *Journal of Experimental Botany*, 53(367), 333-340.
[68] Mickovski, S., van Beek, L., and Salin, F. (2005). "Uprooting of Vetiver Uprooting Resistance of Vetiver Grass (<i>Vetiveria zizanioides)." *Plant and Soil*, 278(1), 33-41.
[69] Hamza, O., Bengough, A. G., Bransby, M. F., Davies, M. C. R., and Hallett, P. D. (2007). "Mechanics of root-pullout from soil: A novel image and stress analysis procedure
Eco-and Ground Bio-Engineering: The Use of Vegetation to Improve Slope Stability." A. Stokes, I. Spanos, J. E. Norris, and E. Cammeraat, eds., Springer Netherlands, 213-221.
[70] Mickovski, S. B., Bransby, M. F., Bengough, A. G., Davies, M. C. R., and Hallett, P. D. (2010). "Resistance of simple plant root systems to uplift loads." *Canadian Geotechnical Journal*, 47(1), 78-95.

[71] Retzlaff, W., Celik, S., Morgan, S., Graham, M., and Luckett, K. "Into the Wind - Wind Tunnel Testing of Green Roof Systems." *Proc., Cities Alive: 8th Annual Green Roof and Wall Conference and Proceedings*, 21.
[72] Wanielista, M., Minareci, M., Catbas, N., and Hardin, M. (2011). "Green roofs and wind loading." University of Central Florida, 200.
[73] FEMA (2005). "Floridians Receive More than $4.2 Billion in Disaster Aid." <http://www.fema.gov/news/newsrelease.fema?id=16722>. (June 5, 2012, 2012).
[74] (FEMA), F. E. M. A. (2005). "Mitigation Assessment Team Report: Summary Report on Building Performance 2004 Hurricane Season."Washington, D.C., 68.
[75] (FEMA), F. E. M. A. (2005). "Mitigation Assessment Team Report: Hurricane Charley in Florida." FEMA, Washington, D.C., 68.
[76] Miller, C. (2007). "Design Strategies to Address Wind Uplift and Scour in Green Roofs." Roofscapes, Inc., Philadelphia, PA, 3.
[77] Holmes, J. D. (2007). *Wind Loading of Structures*, Taylor & Francis.
[78] (FLL), F. L. L. e. V. (2008). "FLL Standard - "Guidelines for the Planning, Construction and Maintenance of Green Roofing - Green Roofing Guideline"." Forschungsgesellschaft Landschaftsentwicklung Landschaftsbau e.V. (FLL), Colmantstraße, Bonn, 125.
[79] Global), F. M. G. F. (2011). "1-35: Property Loss Prevention Data Sheets Green Roof Systems." Factory Mutual Global (FM Global), 27.
[80] (ANSI), A. N. S. I., and (SPRI), S. P. R. I. (2010). "ANSI/SPRI RP-14 2010 Wind Design Standard for Vegetative Roofing Systems." SPRI, Waltham, MA, 36.
[81] Kind, R. J., and Wardlaw, R. L. (1985). "Wind tunnel tests on loose-laid roofing systems for flat roofs." Carleton UniversityNational Research Council Ottawa, Canada, 6.
[82] Smith, T. (2010). "Mapping the 2010 wind changes." National Roofing Contractors Association (NRCA), 5.
[83] Prevatt, D. O., Acomb, G. A., Masters, F. J., Vo, T. D., and Schild, N. K. (2011). "Wind Performance Study for Extensive and Intensive Green Roof Modules." University of Florida, Gainesville, FL, USA, 38.
[84] Wanielista, M. P., Hardin, M., and Kelly, M. "A water quality assessment of two green roof stormwater treatment systems." *Proc., World Environmental and Water Resources Congress 2008: Ahupua'a, May 12, 2008 - May 16, 2008*, American Society of Civil Engineers, Environmental and Water Resources Institute of ASCE.

APPENDIX A: STANDARD COURSE DEPTHS FOR VARIOUS TYPES OF VEGETATION



((FLL), 2008)

APPENDIX B: CALCULATING COVERAGE RATIO IN ADOBE PHOTOSHOP

1. Select the Polygonal Lasso tool (in tool palette to left of workspace).

2. Make selection of area of interest.

3. Choose Select > Color Range.

4. Set the following options:
   - Click the Selection radio button
   - Selection Preview to Black Matte
   - Click Add to Sample Button

5. Click the plant(s) by making selections (as you make these selections the plant should become more visible

6. To add additional tones to the selection:
   - Continue to click the shaded regions of the plant
   - Also move the Fuzziness slider to the right to increase selection
     - Do this slowly and stop to add different tones of the plant

7. To make sure desired regions are fully selected, do the following, and click ok.
   - Increase Fuzziness till unwanted regions of the image are visible (such as soil artifacts)
   - Then move slider to position where unwanted regions are not visible any longer

Now only the plants are selected

8. Review image closely to make sure only plants are selected. If part of the plants are not selected use the Quick Selection Tool or the Magic Wand Tool (hold down shift). When using Magic Wand you may change the tolerance to make your selection more precise.

9. Find number of pixels in selected region using the Histogram:
   - If Histogram window is not open in the Edit workspace or the Panel Bin, choose Window > Histogram.
   - At top right corner of window select the Panel menu and click Expanded View and then click Show Statistics
   - If the Cache Data Warning icon is displayed at the top right hand corner of the graph (appears as a triangle centered around an exclamation mark), hit the Uncached Refresh button (appears as a circle composed of two arrows)
   - The number of pixels will be displayed at the bottom left hand corner of the window

10. Use this method to find the pixels that represent the plants. Record. Select total area (including soil and plants) using the Polygonal Lasso tool, and find number of pixels for this region using step 8. Record.

11. Determine Coverage Ratio:
    - Divide the number of pixels of the plants by the number of pixels of the total area. Record values. Repeat for each image

Deviations from Procedure:

For the before picture of NS-1 we calculated the ratio between pixels of soil and that of total are and subtracted that from 1 to find the coverage ratio because the plants covered >80% of the area.
This strategy was used for the images:

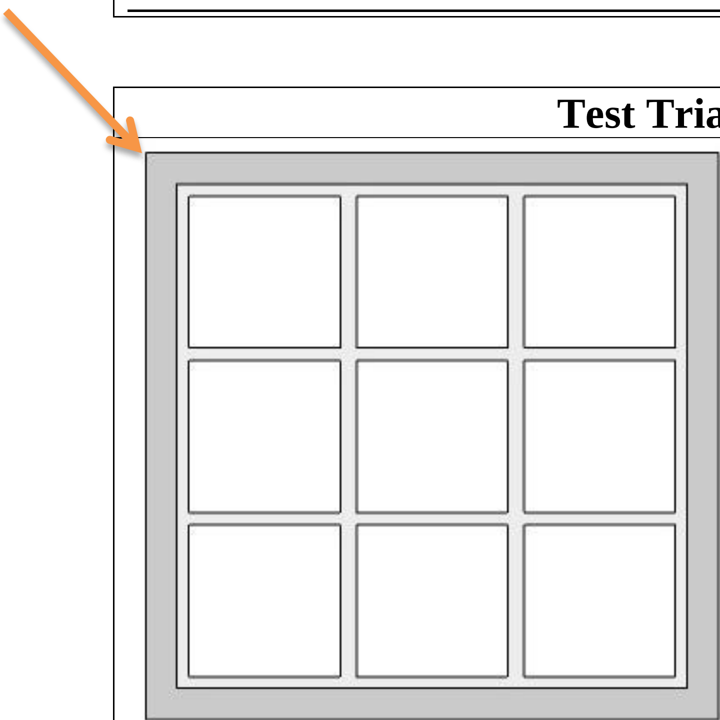
- NS-1 both before and after
- NS-2 both before and after
- S-S1 both before and after
- S-S2 both before and after

APPENDIX C: TEST TRIAL DATA SHEETS

Module Weighing Data Sheets							
Name: ______________________________ Date: ___/___/2012				Pre-Time: __:__AM/PM	Post-Time: __:__AM/PM	Soil-Time: __:__AM/PM	
Media Depth	**Test ID**	**Module #**	**Plant Height (Tall/Short/ Mixed)**	**Pre-Test Weight (lbs)**	**Post-Test Weight (lbs)**	**Soil Sample Taken? (Y/N)**	
		1					
		2					
		3					
		4					
		5					
		6					
		7					
		8					
		Unplanted					
Notes:							

____

Test Trial Data Sheet



Circle one: BIP Modular

Date: ___/___/2012

Time: ___:___ AM/PM

Test Trial:

____

Failure? Y___ N___

Time of Failure: ___ min ___ s

Name:

____

Notes:

____

____

____

____

____

____

____

____

____

____

____

____

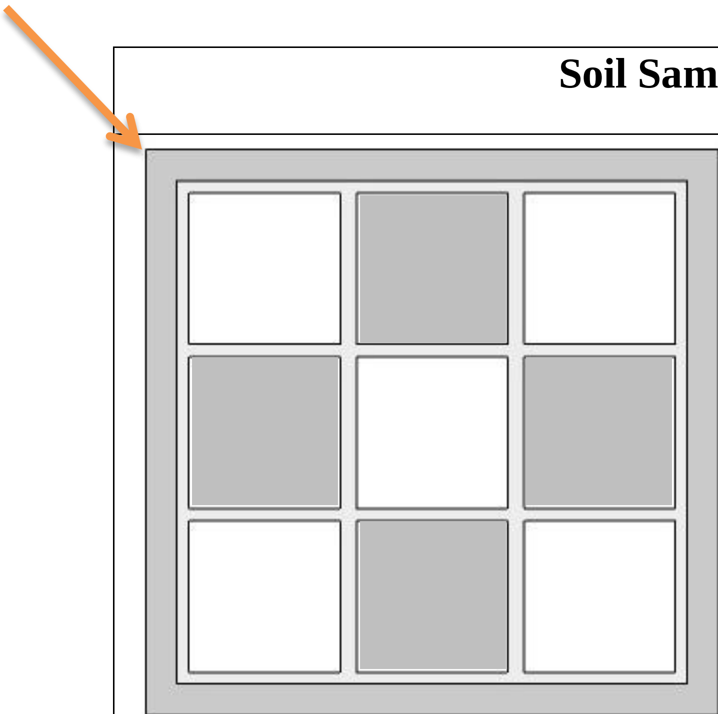
____

____

____

____

Soil Sample Labeling



Date: ___/___/2012
Time: ___:___ AM/PM

Test Trial:

Name:

Notes: (Top left to right: 1, 3; Center: 5; Bottom left to right: 7, 9)

APPENDIX D: MOISTURE CONTENT DATA SHEET

Soils oven dried at 105 C for 24hrs
% moisture calculated on a mass/mass basis
Overall weight of soil sample provided in Column 2
Soil subsample wet weight in Column 4
Soil subsample dry weight in Column 5
Soil % moisture content in Column 8

Sample ID	Bulk Bag + Sample, g	Weigh Boat, g	Wet Soil + weigh boat, g	Dry Soil + Weigh boat, g	Wet Soil, g	Dry Soil, g	% moisture m/m
S-T1-1	221.0	1.01	17.67	14.23	16.66	13.22	20.6%
S-T1-3	141.2	1.01	15.97	12.53	14.96	11.52	23.0%
S-T1-5	242.0	1.01	23.79	17.83	22.78	16.82	26.2%
S-T1-7	195.4	0.96	18.92	14.79	17.96	13.83	23.0%
S-T1-9	232.0	1.01	23.62	17.60	22.61	16.59	26.6%
S-T2-1	212.6	1.02	25.41	20.07	24.39	19.05	21.9%
S-T2-3	243.1	1.01	21.06	16.14	20.05	15.13	24.5%
S-T2-5	231.3	1.02	22.58	17.04	21.56	16.02	25.7%
S-T2-7	272.4	1.01	22.79	16.89	21.78	15.88	27.1%
S-T2-9	190.7	1.00	19.77	14.19	18.77	13.19	29.7%
S-S1-1	201.8	1.00	20.37	15.62	19.37	14.62	24.5%
S-S1-3	275.7	1.02	27.28	18.93	26.26	17.91	31.8%
S-S1-5	218.5	0.98	21.58	14.99	20.60	14.01	32.0%
S-S1-7	250.9	1.00	24.61	17.86	23.61	16.86	28.6%
S-S1-9	286.6	1.02	21.70	15.19	20.68	14.17	31.5%
S-S2-1	220.4	1.00	19.88	14.91	18.88	13.91	26.3%
S-S2-3	267.3	1.00	20.87	15.11	19.87	14.11	29.0%
S-S2-5	286.9	1.03	25.38	18.01	24.35	16.98	30.3%
S-S2-7	234.1	1.00	22.00	16.11	21.00	15.11	28.0%
S-S2-9	251.8	0.98	23.52	16.54	22.54	15.56	31.0%
S-M1-1	227.7	1.01	19.10	14.40	18.09	13.39	26.0%
S-M1-3	218.5	0.96	26.09	18.47	25.13	17.51	30.3%
S-M1-5	199.2	0.99	24.69	17.45	23.70	16.46	30.5%
S-M1-7	168.5	1.02	24.32	18.27	23.30	17.25	26.0%
S-M1-9	106.8	1.07	19.94	14.60	18.87	13.53	28.3%
T2-1	163.4	1.05	22.93	18.39	21.88	17.34	20.7%
T2-2	128.2	1.03	17.13	14.37	16.10	13.34	17.1%
T2-3	124.5	1.01	20.25	16.05	19.24	15.04	21.8%
T2-4	134.6	0.97	18.69	14.61	17.72	13.64	23.0%

T2-5	124.2	1.00	20.76	15.92	19.76	14.92	24.5%
T2-6	137.8	1.02	22.70	17.60	21.68	16.58	23.5%
T2-7	163.1	1.01	20.62	16.34	19.61	15.33	21.8%
T2-8	153.8	1.05	19.54	15.70	18.49	14.65	20.8%
T2-9	116.4	1.00	18.74	15.46	17.74	14.46	18.5%
T5-1	119.9	1.01	22.69	20.31	21.68	19.30	11.0%
T5-2	167.4	1.02	23.61	18.87	22.59	17.85	21.0%
T5-3	196.8	0.99	20.88	16.60	19.89	15.61	21.5%
T5-4	144.6	0.99	24.73	20.92	23.74	19.93	16.0%
T5-5	206.7	1.00	22.82	17.04	21.82	16.04	26.5%
T5-6	185.5	0.98	22.28	17.10	21.30	16.12	24.3%
T5-7	114.6	0.98	17.74	15.93	16.76	14.95	10.8%
T5-8	142.2	1.01	24.62	21.01	23.61	20.00	15.3%
T5-9	231.1	0.98	24.00	19.31	23.02	18.33	20.4%
T6-1	134.8	1.01	17.50	14.68	16.49	13.67	17.1%
T6-2	211.8	0.99	21.77	16.45	20.78	15.46	25.6%
T6-3	174.5	0.99	21.48	17.24	20.49	16.25	20.7%
T6-4	126.2	1.01	21.55	17.42	20.54	16.41	20.1%
T6-5	176.0	1.01	19.63	15.13	18.62	14.12	24.2%
T6-6	261.4	1.00	22.48	17.70	21.48	16.70	22.3%
T6-7	124.2	1.00	22.44	16.86	21.44	15.86	26.0%
T6-8	194.2	0.99	22.16	17.25	21.17	16.26	23.2%
T6-9	220.6	1.01	22.63	17.98	21.62	16.97	21.5%
T7-1	118.1	0.99	18.85	14.64	17.86	13.65	23.6%
T7-2	87.6	0.99	21.06	16.41	20.07	15.42	23.2%
T7-3	177.6	1.02	20.60	15.18	19.58	14.16	27.7%
T7-4	208.3	1.01	22.89	17.24	21.88	16.23	25.8%
T7-5	196.0	1.01	23.03	16.43	22.02	15.42	30.0%
T7-6	211.3	1.02	22.45	16.16	21.43	15.14	29.4%
T7-7	164.3	1.03	28.74	20.13	27.71	19.10	31.1%
T7-8	119.5	1.02	21.55	16.19	20.53	15.17	26.1%
T7-9	187.8	1.00	24.91	19.58	23.91	18.58	22.3%
D-4"-5/T2-2	123.9	1.00	20.06	17.60	19.06	16.60	12.9%
D-4"-2/T2-3	124.4	0.95	20.17	17.08	19.22	16.13	16.1%
D-4"-3/T2-5	107.3	1.03	19.17	16.33	18.14	15.30	15.7%
D-4-5/T2-8	127.0	1.00	19.70	15.36	18.70	14.36	23.2%
D-4-1/APE LAN T2-9	164.7	1.01	20.58	17.49	19.57	16.48	15.8%
W-4-1/T1-1 Wet	180.9	0.98	26.96	17.52	25.98	16.54	36.3%
N-T1-1	225.2	1.03	21.34	16.50	20.31	15.47	23.8%
N-T1-3	192.8	1.00	25.24	19.31	24.24	18.31	24.5%
N-T1-5	174.8	0.98	22.89	16.63	21.91	15.65	28.6%

N-T1-7	215.9	1.01	20.44	15.64	19.43	14.63	24.7%
N-T1-9	164.3	0.97	19.47	14.70	18.50	13.73	25.8%
N-T2-1	325.0	0.97	20.35	16.18	19.38	15.21	21.5%
N-T2-3	256.2	0.99	23.64	17.29	22.65	16.30	28.0%
N-T2-5	247.5	0.96	23.82	17.94	22.86	16.98	25.7%
N-T2-7	185.6	1.02	23.99	18.05	22.97	17.03	25.9%
N-T2-9	232.6	1.00	24.65	18.32	23.65	17.32	26.8%
N-S1-1	199.1	0.99	25.37	20.21	24.38	19.22	21.2%
N-S1-3	175.5	1.00	21.46	16.54	20.46	15.54	24.0%
N-S1-5	213.3	1.01	24.09	17.69	23.08	16.68	27.7%
N-S1-7	142.2	1.00	22.71	18.37	21.71	17.37	20.0%
N-S1-9	264.5	1.01	19.40	14.69	18.39	13.68	25.6%
N-S2-1	133.5	1.00	25.77	22.05	24.77	21.05	15.0%
N-S2-3	238.2	0.98	23.82	18.16	22.84	17.18	24.8%
N-S2-5	266.4	0.97	18.07	13.94	17.10	12.97	24.2%
N-S2-7	201.6	1.01	20.25	16.46	19.24	15.45	19.7%
N-S2-9	255.2	0.98	20.09	15.86	19.11	14.88	22.1%