Wind Barrier Development for Higher Ground Farm

David Frederick, Joshua Mace, David Swenarton

Worcester Polytechnic Institute

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ABSTRACT

Urban rooftop farming benefits cities through energy conservation, storm water management, and increasing urban food security. However, crops grown on urban rooftops are exposed to harsher winds than their ground-level counterparts, resulting in reduced crop yield and profit for farmers. This project designed and built wind barriers to protect crops on Higher Ground Farm, a rooftop farm in Boston, MA. A user manual for the barriers has also been created to serve as a resource for other urban rooftop farmers.

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Many members of the WPI staff and faculty assisted us with the barrier testing performed in Worcester. We would like to thank Daniel Sarachick of WPI Environmental Health and Safety, who met with us to ensure that our testing followed safety regulations. We would also like to thank Chief Martunas and Sgt. Bueno of WPI Police for giving us approval for the barrier testing and ensuring we had access to the testing location. Additionally, we would like to thank Al Carlsen of WPI Facilities for setting up barricades at the testing location. We would especially like to thank Alfredo DiMauro of WPI Facilities. He was incredibly helpful and supportive when we were initially trying to get approval for testing, and he put us in contact with everyone we needed to consult.

Many WPI faculty members assisted us with planning the project and writing this report. We would like to thank Laura Robinson of the WPI Gordon Library for helping us find sources. We would also like to thank Professor Robert Traver, who helped us get started on the project in ID2050. Professor Traver edited numerous drafts of several sections of this paper and helped us create a proper foundation for the project. We would especially like to thank Dr. Lisa Stoddard and Dr. Aaron Sakulich for advising this project. Stoddard and Sakulich gave us timely feedback on our writing throughout the year, and motivated us to output our best work. They went above and beyond the normal expectations of advisors by helping us gather and transport supplies, and putting us in contact with several people who provided us with supplies and feedback on our project.

Lastly, we would like to thank John Stoddard of Higher Ground Farm for sponsoring this project. Mr. Stoddard was always willing to take time out of his busy schedule to meet with us and assist us with our work.

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Executive Summary

Rooftop farming is a growing industry that provides cities with local produce and environmental benefits, such as reduced energy costs and improved storm water management. However, rooftop farms also face several challenges that hinder their profitability. One of these challenges is wind damage to crops. Wind damages crops through cell abrasion by bursting epidermal cells and by damaging the plant's outer protective wax layer. This damage impacts the plant's ability to control water loss, which leads to windburn, reduced crop size, and smaller harvests (Brandle, 2012).

This project is sponsored by John Stoddard of Higher Ground Farm, who has struggled with wind-related crop damage and associated financial losses since his first growing season in 2014. Specifically, tomato plants at the farm have had stalks broken by wind, and smaller plants such as arugula and green beans have experienced windburn on their leaves. Drawing on interviews conducted with other rooftop farmers, wind barrier experts, as well as an analysis of relevant published literature, we found that there is not a wind barrier protection system designed for the unique needs of rooftop farms. Meeting these needs requires wind barriers that are compact, durable, easy to assemble and deconstruct, and reduce wind speeds without creating turbulence.

In this project, we designed, built, tested, and supplied Stoddard with a system of wind barriers that will protect all of the crops on his farm. There is a lack of published information about dealing with wind damage on rooftop farms. Because of this, we also developed a guide on how to build, use, and maintain different types of wind barriers for rooftop farmers. This guide provides rooftop farmers with an accessible and simple resource to help them compare several

barrier designs, select designs based on the conditions at their farm, and assemble the chosen barriers.

I. Project Goal, Objectives, and Methodology

The goal of this project was to design wind barriers that provide effective protection for crops at Higher Ground Farm and other urban rooftop farms. In order to attain this goal, we developed three objectives: 1) understand the unique conditions on rooftop farms that impact wind behavior and wind damage; 2) analyze existing ground-level wind barrier technology and modify it to meet the needs of our sponsor's farm; and 3) further improve the wind barrier designs by creating and testing wind barrier prototypes.

Objective 1 Methodology: Understand Unique Conditions on Rooftop Farms That Impact Wind Behavior and Wind Damage

To meet the first objective, we went to our sponsor's farm to engage in participant observation, collect wind data measurements, and to interview him. The goal of these activities was to gain an understanding of the farm layout and daily activities on the farm, and to understand our sponsor's concerns about how wind was affecting his farm. The purpose of collecting wind data was to understand the unique environmental conditions at Higher Ground Farm. Wind velocity and direction measurements were taken with an anemometer to determine general wind patterns on the roof. These measurements also helped to determine the locations on the farm that are most affected by wind, as well as the differences between the roof's microclimate and the outside environment.

We also conducted semi-structured interviews with other urban rooftop farmers, and we conducted a focus group with past Higher Ground Farm interns. The purpose of these activities was to gain additional perspectives on wind damage to crops, space constraints, and other unique problems present on rooftop farms, such as planting and harvesting in windy conditions.

Objective 2 Methodology: Analyze Existing Ground-Level Wind Barrier Technology and Modify it to Meet the Needs of our Sponsor's Farm

To meet the second objective, we analyzed secondary data, conducted semi-structured interviews with urban rooftop farmers and wind barrier experts, and conducted a focus group with past Higher Ground Farm interns.

Secondary data provided information about effective ground-level wind barriers. We then modified these wind barrier designs and their properties to enable them to be effective on rooftops based on the information gathered for the first objective. This modification resulted in three barrier designs: 1) ivy walls to protect tall crops, consisting of a wooden lattice and supported frame with ivy grown on the face, 2) row covers with a securing mechanism to protect short crops, and 3) tall grass barriers. The goal of the interviews with other rooftop farmers was to learn how wind uniquely impacts their individual farms, and what measures each farm has taken to protect their crops from wind damage. This information allowed our barrier designs to be tailored not only for Higher Ground Farm, but for future application on other rooftop farms. The goal of the interviews with wind barrier experts was to receive feedback on our barrier designs and our plans for prototype testing. Their feedback improved the designs by pointing out flaws and suggesting solutions to those flaws.

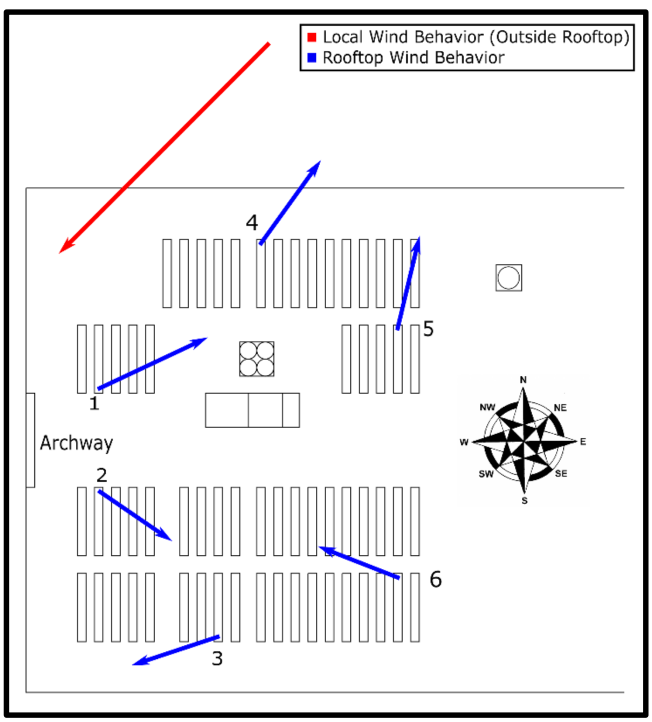
Objective 3 Methodology: Further Improve the Wind Barrier Designs by Creating and Testing Wind Barrier Prototypes

To meet the third objective, we created wind barrier prototypes and conducted testing to evaluate barrier durability and effectiveness, and to reveal design flaws that were not previously considered. We collected data through qualitative observations and quantitative wind measurements using an anemometer. This testing was performed on the top level of the six-story tall WPI-owned Gateway parking garage. The testing of the ivy wall barriers focused on the durability of the structures under heavy wind conditions, and their effectiveness at reducing wind speeds. The testing for the row cover design was focused on the functionality of the mechanism that secured the covers to the raised crop bed to ensure that it was functional for farmers planting and harvesting crops in windy conditions.

II. Results

Objective 1 Results: Understand Unique Conditions on Rooftop Farms That Impact Wind Behavior and Wind Damage

Wind speed and directions measurements revealed that wind speeds in the microclimate of the farm space are reduced compared to wind speeds outside the rooftop. This is due to the parapet wall that surrounds the farm. However, wind direction on the rooftop was shown to be



unpredictable. To the left is a diagram showing the wind speeds and directions measured on the farm. Wind speed is indicated by the arrow lengths. From this, we learned that the wind barriers would have to protect crops from all angles. Interviews with other urban rooftop farmers revealed that another farm in Toronto has experienced wind damage to their tomato plants in the past. This showed that the wind problem at

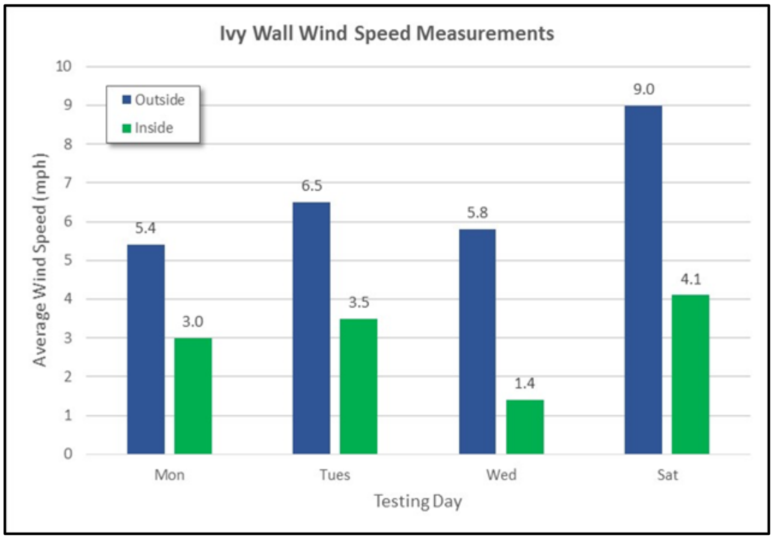
Higher Ground Farm is not unique.

Objective 2 Results: Analyze Existing Ground-Level Wind Barrier Technology and Modify it to Meet the needs of our Sponsor's Farm

Initial barrier designs were based on information gathered on barriers designed for ground-level farms. This information revealed that porous barriers were effective because they reduce wind speeds without creating areas of turbulence downwind. Organic barriers, or barriers made from plant material, are also effective because plants have a large surface area, porosity, and flexibility that allow them to absorb a lot of energy from wind. Based on this, the three previously introduced initial barrier designs were conceived. These designs were then discussed with wind barrier experts in interviews, and with a focus group of past interns at Higher Ground Farm. Based on their feedback, the barrier designs were improved. The ivy walls were changed to be more structurally sound, and made to be easily disassembled. The testing plan for row covers was modified to ensure that the securing mechanism made the covers easy to use in windy conditions. The species of tall grass for the grass barrier was changed from rush wheatgrass to little bluestem grass to improve the barrier's durability and reduce the risk of the grass seeding itself in planter rows.

Objective 3 Results: Further Improve the Wind Barrier Designs by Creating and Testing Wind Barrier Prototypes

Barrier prototype testing verified the effectiveness of our designs. Wind speed measurements taken both inside and outside an ivy wall enclosure revealed that the ivy wall reduces wind speeds by 55% on average. Below is a graph showing the average wind speeds inside and outside the ivy wall enclosure on each testing day. A four-day trial with a reduced-porosity ivy wall left in the testing environment showed that the design is structurally sound, and that the barrier is not at risk of tipping over in strong winds provided that there is at least 200 pounds of soil on the baseplate.



This weight in soil would fill the three milk crates intended to hold the ivy plant. Testing of the row cover securing mechanism showed that it is effective at stopping the row covers from flapping in wind. This will prevent the covers from impeding farm work.

III. Recommendations

A. Recommendations for Higher Ground Farm

Our barriers were designed to address the unique conditions present at Higher Ground Farm. Among all of the crops at Higher Ground Farm, tomato plants are experiencing the most severe wind damage. To address this, we recommend constructing ivy walls and placing them around the tomato planter rows. Ivy walls have the height needed to fully protect tall tomato plants, and the stability to stay upright in strong wind conditions. The barriers should surround the planter rows on all sides to adequately protect the tomato plants, given the unpredictable and multi-directional wind conditions at the farm. Based on the dimension of all planter row sections, 10 ivy wall barriers would be the maximum number needed for a growing season. The cost of constructing 10 ivy wall barriers would be $896.86.

We recommend that John Stoddard use row covers to protect the remaining planter rows. These rows all contain plants that grow close to the soil, and row covers are a cheap solution that provide complete coverage and take up minimal space. The cost of constructing row covers for these planter rows would be $1240.32.

B. Recommendations for Other Rooftop Farms

We recommend that rooftop farmers who are experiencing wind damage to their crops consider constructing some of the barriers developed in this project, depending on their specific needs and conditions on their farms. Ivy walls should be used to protect tall crops like tomato plants. They have been designed to make tight corners when placed next to each other so that they can be used to completely enclose a group of crops. For crops that are low to the ground, we recommend using row covers or tall grass barriers, depending on the features of the rooftop. For rooftop farms that lack excess space or have cramped pathways between crop rows, we recommend row covers because they fit directly on top of crop rows and don’t take up any extra space. Tall grass barriers are also a viable option to protect low-growing crops. Farmers may prefer to use tall grass barriers if they have a small number of workers available to set up the barriers, as they are less cumbersome and time consuming to set up than row covers. Before constructing grass barriers, farmers should take measurements to ensure that they will not take up too much space and obstruct walking paths.

IV. CONCLUSION

Through this project, we have created a resource for urban rooftop farmers who experience wind-related crop damage. By doing so, we are filling a gap in the literature on 1) how wind behaves and damages crops on urban rooftop farms, and 2) wind barriers suitable for the unique conditions of urban rooftop farms. Using our barrier designs to mitigate wind damage will make Higher Ground Farm and other urban rooftop farms more profitable by protecting their crops from wind damage and associated financial losses. Increasing profits for urban rooftop farmers will help to ensure that they can continue to provide cities with the energy conservation, storm water management, and food security benefits that come from rooftop farms.

CONTRIBUTIONS AND AUTHORSHIP

David Frederick was the primary author of the user manual and the rejected wind barrier designs appendix. He also contributed writing for the introduction and results section. In addition, he was the primary photographer of the project, providing most of the photographs in the report. He was also involved with the interview process. David was a key contributor to the barrier designs, and was responsible for all of the barrier sketches in the report. He was also responsible for the construction of the prototype barriers, and was an active part of the testing process.

Joshua Mace was the primary author of the results and recommendation sections. He was responsible for the data analysis and graphs in the results section. He also contributed a significant amount to the writing and editing of the literature review and methodology. In addition, he was an active part of the interview process, and conducting a majority of the interviews and the focus group. He was also an active part of the testing process.

David Swenarton was the primary author of the introduction, executive summary, and conclusion. He also contributed a significant amount to the writing and editing of the literature review, methodology, and recommendation section, and contributed to the other sections of the report through edits and revisions. In addition, he was an active part of the interview process by transcribing a majority of the interviews and the focus group. He was also an active part of the testing process.

INTRODUCTION

Urban rooftop farming is a growing industry that supplies cities with produce by cultivating crops on previously unused city rooftops. Rooftop farms benefit buildings in several ways. These benefits include reducing energy consumption, improving storm water management, improving city air quality, and reducing carbon emissions. There are many advantages that rooftop farms can bring to a city, but they also face challenges.

Water consumption, unique pests, soil transportation, rooftop weight and space constraints, and wind can all hinder a rooftop farm's development. Wind specifically can damage crops at a cellular level, cause soil erosion, and reduce produce marketability. Our sponsor, John Stoddard, operates Higher Ground Farm, a rooftop farm in Boston, MA. Higher Ground Farm regularly struggles with wind damage to crops, resulting in crop damage and reduced profits. Current literature and research on wind dynamics, associated crop damage, and wind barriers focuses on ground-level farms in rural areas. However, there is a lack of published information about rooftop wind dynamics or wind barriers for urban rooftop farms. The goal of this project was to design wind barriers that provide effective protection for crops at Higher Ground Farm and other urban rooftop farms.

This goal was accomplished by satisfying three objectives. The first objective was to understand the unique conditions on urban rooftop farms that impact wind behavior and wind damage. The second objective was to analyze existing ground-level wind barrier technology and modify it to meet the needs of our sponsor's farm and other rooftop farms. The third objective was to improve the wind barrier designs by creating and testing wind barrier prototypes.

This report is divided into several sections. First, the literature review describes the benefits and challenges of rooftop farms, the effects of wind damage, as well as wind dynamics and wind barriers. After the literature review, the methodology describes how we gathered the information needed to meet each objective, including semi-structured interviews, focus groups, secondary data collection, design iterations, and prototype testing. The results section then explains the results of the interviews, data collection, and tests performed, and explains how each result affected relevant barrier designs. The recommendation section then provides a thorough recommendation for John Stoddard to protect his crops from wind damage. This section also provides more general recommendations for other rooftop farms. To conclude, the implications of this work on rooftop farms as a whole are explained.

LITERATURE REVIEW

This project developed a system to reduce wind damage on rooftop farms. This section starts by discussing the benefits of rooftop farming. Next, the challenges of rooftop farming are addressed, with a focus on wind damage. Third, wind barrier technology is discussed.

I. BENEFITS OF ROOFTOP FARMS

Urban rooftop farms increase local food security and access to fresh, nutritious produce. Urban rooftop farms can also benefit cities through storm water management, energy conservation, and the reduction of carbon emissions.

City storm water management is important to reduce pollution and flooding. When precipitation reaches impervious surfaces such as concrete, asphalt, or thermoset membranes on the ground or on a rooftop, it flows over the surface and picks up debris and pollutants. This is known as runoff. Common pollutants from rooftop runoff include heavy metals, polycyclic aromatic hydrocarbons, pesticides, and microbes from bird and insect feces (Freshwater, 2013). Runoff can become a problem for cities like Boston with combined sewage overflow systems during periods of heavy precipitation ("Combined Sewer Overflow", 2016). Combined sewage overflow is a form of wastewater management in which sewage and rainwater are carried through the same pipe, rather than staying separated. During periods of heavy precipitation, these systems can be filled beyond their capacity, in which case wastewater flow is diverted into local bodies of water. When this happens, pollutants from runoff are dumped into these bodies of water ("Green Roof Benefits", n.d.). Rooftop farms help cities manage runoff by absorbing and filtering precipitation. By absorbing precipitation, rooftop farms reduce the total volume of rainwater that will reach impervious surfaces. This in turn reduces the amount of pollutants that rain will carry to storm drains and sewers. *Figure 1* illustrates how plants affect runoff.

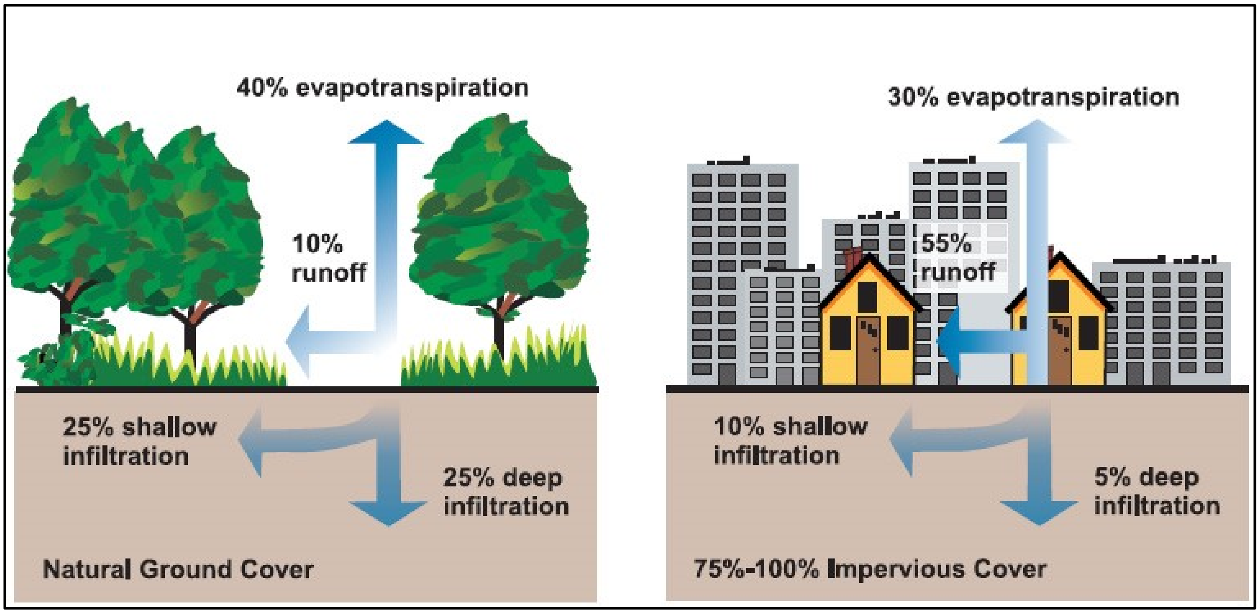


Figure 1: **Plant Cover vs Impervious Cover (City, 2012)**

Soil filters out existing pollutants in rainwater, as heavy metals will bind to soil particles (Freshwater). Rooftop farms also return water to the atmosphere through evapotranspiration. This water has been filtered by the soil and through the plant, so this has the effect of reintroducing cleaner water to the atmosphere.

Rooftop farms also conserve a significant amount of energy. Urban areas with high population and structure density create environments with increased temperature. This phenomenon is known as the urban heat island effect ("Urban Heat Island", n.d.). This is caused by dark-colored rooftops absorbing the sun's radiation. Rooftop plants and soil absorb heat and lower roof surface temperatures in warm months, and act like insulators to stop heat from escaping during winter ("Green Roof Benefits", n.d.). Internal building temperatures can be 3-4°C (5-7°F) cooler than buildings with empty rooftops in the summer, reducing energy costs and related emissions (Thomaier, 2015). *Figure 2* contains a graph with data comparing temperatures on a normal roof to temperatures on a green roof.

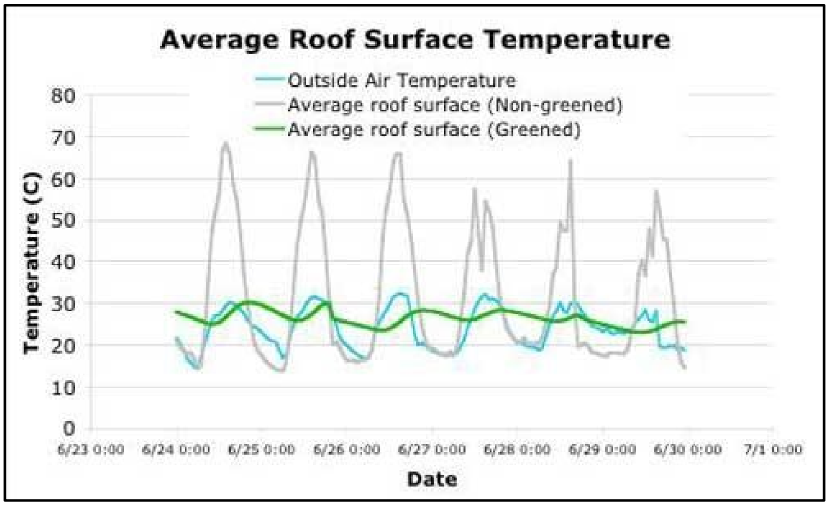


Figure 2: **Rooftop Temperature Comparison ("Center for Green", 2005)**

Keeping buildings cooler in the summer and warmer in the winter results in reduced usage of air conditioners and heating systems. This effect is strong enough that annual city-wide energy consumption could be reduced by 15% if rooftop agriculture becomes widespread (Thomaier, 2015).

Additionally, rooftop farms help to reduce carbon emissions. Crop photosynthesis reduces the level of carbon dioxide in the air by converting it into oxygen. The reduced travel distance for farm produce also significantly decreases the carbon emissions normally caused by transport vehicles travelling long distances to deliver food in most cases ("Green Roof Benefits", n.d.).

II. Challenges of Rooftop Farming

Rooftop farms face several challenges. Some of these challenges are experienced by all farms, but rooftop farms face additional unique challenges. These challenges include water consumption, predators, transporting soil to the roof, rooftop weight constraints, and wind. In this section, we summarize these issues and their impacts on rooftop farms, with a focus on wind damage.

Despite being partially irrigated by rainwater, all farms use a lot of water, and rooftop farms are not an exception. Water is more expensive in cities than in rural areas (Sanyé-Mengual, 2015). This cost affects farm revenue. As such, water consumption hinders urban agriculture. Predators and pests can also hinder crop growth and yield. Pests can eat the plants, which stunts crop growth, and they can eat the produce itself. These pests include maggots, aphids, other insects, and birds (Novak, 2016). Higher Ground Farm specifically has had problems with seagulls, a pest unique to the farm's coastal location and to urban rooftop farms. By reducing crop yield, pests reduce the revenue of rooftop farms, which makes maintaining a successful rooftop farm more difficult. Rooftop farms also require a large amount of soil. While it may seem trivial, transporting soil to a rooftop can be quite challenging. A crane is often required, which is an additional expense that hinders the farm's overall profit (Levenston, 2010). The structural integrity of the roof itself also presents challenges. The weight capacity of rooftops limits the amount of soil that can be used, thus limiting the number of crops. Additionally, useful tools such as pallet jacks and tractors are too heavy to be used on rooftops, meaning that rooftop farm work is limited to manual labor by farm workers.

Wind is another challenge experienced by both rooftop farms and farms on the ground. While there is research and literature that analyze wind dynamics, damage, and barriers for crops on the ground, there is a lack of literature that focuses on the unique wind conditions and potential barriers for rooftop farms. This project focuses on wind damage, an issue that has affected our sponsor's crops and is one of his primary concerns. This section discusses research on wind dynamics and damage for farms on the ground. Our research aims to build on and add to this literature by analyzing wind on roof top farms.

Wind damages crops through cell abrasion, soil erosion, and reduced produce marketability. An experiment performed in a 3.5 m/s wind tunnel showed that exposure to wind damages crops at a cellular level. Burst epidermal cells, cracking, and redistribution of the protective wax layer that coats the outside of the plants was observed. This damage primarily impacts the plant's ability to control water loss, which can lower crop yields and reduce both the size and volume of harvests (Brandle, 2012). For example, in one case, wind damage caused blemishes and bruises on a commercial kiwifruit farm. This damage left 58% of the harvested fruits unmarketable, causing significant revenue losses (McAneney, 1984). *Figure 3* shows wind damage to spinach leaves at Higher Ground Farm.

***Figure 3*: Wind Damage to Spinach Leaves**

Exposure to wind also causes soil erosion. Erosion can damage plants by reducing the anchorage provided by roots, reducing the nutrients collected by roots, and increasing the number of particulates in the air (Brandle, 2012). Wind erosion is generally present when the crops, soil, and land are under specific conditions that allow erosion to occur. Loose, granulated soil without vegetation cover causes soil to erode more easily. A large, flat farming area with moderate exposure to wind will also be more affected by erosion (Brandle, 2012). Soil erosion requires regular maintenance, and new soil must be added. This increases the workload and financial investment of farmers. Rooftop farmers are likely to be particularly vulnerable to this issue, as they typically work on large, flat surfaces with moderate exposure to wind. In order to support urban rooftop agriculture, a solution that protects crops from wind is necessary.

III. Wind Barrier Technology

Current wind barrier technologies are diverse, and variations in physical design properties alter how wind barriers manage and mitigate the effects wind has on crops. In this section, several types of wind barriers, their properties, and their impact on crops are discussed. This collection of research was focused on non-rooftop farms in rural areas, as there is a lack of data on wind barriers for rooftop farms in urban environments. Therefore, further investigation is needed in this area.

A. Effects on Wind Behavior

Two distinct regions are created behind a wind barrier in an open environment where wind flow is generally perpendicular to the barrier (Brandle, 2012). The first region is characterized by reduced wind speed, turbulence and eddy size. In stable conditions, this "quiet" region is defined as the space below the line that connects the top of the barrier to a point on the ground 8*h* away from the barrier's base, with *h* representing the height of the barrier. In unstable conditions, this imaginary line may be reduced to less than 5*h* away from the base of the barrier (Brandle, 2012). The quiet region represents the protected region of a wind barrier; therefore, understanding this is important when designing wall-type barriers. *Figure 4* is a diagram that depicts this quiet region.

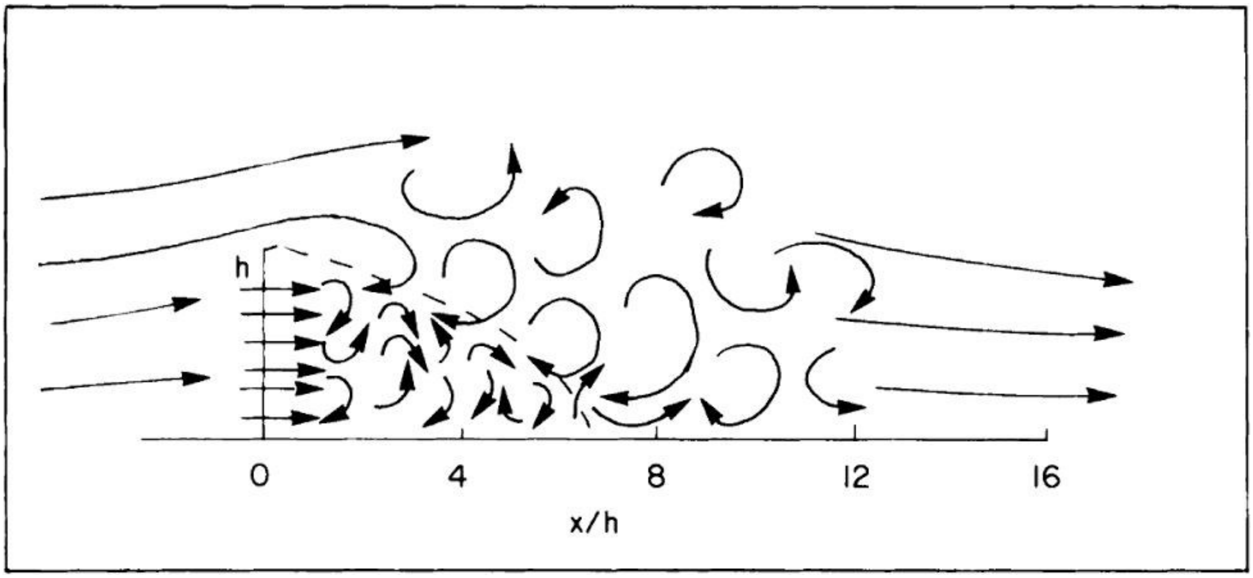


***Figure 4*: Wind Barrier Quiet and Wake Regions (Brandle, 2012)**

The second region, or "wake" region, is characterized by increased turbulence and wind speed; wind speed in this region is still reduced from speeds in front of the barrier. This region is also depicted in *Figure 3*, shown in the area above the dotted line. When low-moisture air is present, the evaporation rate of water inside crops (transpiration rate) can be affected. Plants in the quiet region experience reduced transpiration rates, while plants in the wake region experience increased transpiration rates (Brandle, 2012; Heisler, 1988). Wall-type barriers must be designed with care to prevent turbulence and increased transpiration from damaging crops.

B. Effects on Downwind Environmental Conditions

Research also examines the effects that wind barriers have on temperature, CO_2 concentration, humidity, and water evaporation downwind from the barrier. Wind barriers of multiple types, materials, and sizes have been shown to increase surface and air temperatures within the quiet region, in comparison to the wake region. This warmer area was generally found to be 2°C to 3°C warmer than areas further downwind (Brandle, 2012). Slightly increased temperature behind wind barriers could help crops survive in the early spring and late fall.

Data related to CO_2 concentrations was largely inconclusive, but two trends were identified. The magnitude of changes in CO_2 concentration behind wind barriers seems to be inversely related to wind speed. Multiple studies showed that CO_2 concentration varied by around 10 ppm (parts per million) based on wind speed (Brandle, 2012). This variation is not large enough to significantly affect the growth cycle of the plants.

Humidity levels behind the barrier are directly related to water evaporation levels. During high-speed or turbulent wind conditions, data revealed that the barrier has little to no effect on water evaporation. In calm conditions, evaporation rates and humidity are slightly increased in the quiet region, due to heat and evaporated groundwater that is trapped in the layers of air close to the ground (Brandle, 2012). Because the effects on downwind conditions are minor, wind barriers can provide wind protection without inhibiting crop health or growth.

C. Wall-Type Wind Barriers

Research has also been conducted on the effect that variations in material properties such as porosity, resistance, and drag had on wind behavior. The data shows that a low-porosity material is more effective at reducing wind speeds than a material with near-zero porosity (Brandle, 2012). This is due to a reduced difference in pressure between the quiet region and wake region, lowering the likelihood of recirculating airflow above the barrier. This means that a slightly porous wall-type wind barrier is preferable to a solid wall-type barrier, as solid barriers cause turbulence. Resistance is a term used to describe the difference in air pressure between the front and back of the barrier, and is a function of porosity (Brandle, 2012). As such, it was concluded that a lower resistance is generally preferred. The optimal resistance for a barrier becomes more difficult to determine when dealing with high wind speeds. To sufficiently protect the crops, the minimum acceptable resistance is greater than it would be in less extreme wind conditions (Brandle, 2012). Optimal drag is also difficult to determine. Drag measures how much air momentum is reduced by the material, compared to the maximum possible reduction of momentum. A higher drag coefficient will significantly slow wind speeds, but can lead to more turbulence and eddies behind the barrier (Brandle, 2012). The effectiveness of wall-type wind barriers is determined by their physical properties. These properties can be modified to mitigate their potential flaws.

D. Organic Barriers

It is generally accepted that large natural barriers, like trees, are currently the most effective type of barrier (Brandle, 2012). This is due to their large surface area and variable porosity and flexibility. These properties allow trees to absorb a large amount of energy from wind (Brandle, 2012; Heisler, 1988). This solution, however, is not feasible for rooftop farms. Trees have large root systems that require more volume than any rooftop farm could spare. It is also doubtful that a rooftop would have the structural integrity to support the weight of several trees and the soil required to support them.

The effectiveness of smaller natural barriers is also discussed in “Windbreak Technology”. A study of tall wheatgrass (*Agropyron elongatum*) showed that grass barriers protected downwind crops from both erosion and excess water loss. The wheatgrass was planted in single and double rows at intervals of roughly 15 meters. At 0.3 meters above the ground downwind of the wheatgrass, wind speed was reduced by an average 45%. Crops downwind of the wheatgrass experienced only 6.6% of the wind damage that similar crops in an unprotected environment experienced (Brandle, 2012). Throughout the spring and summer growing season, it was observed that the wheatgrass barriers increased soil temperatures in spring, decreased soil temperatures during the summer, and slowed the evaporation of rainwater from the soil up to a depth of 10 centimeters (Brandle, 2012). Small natural barriers may provide a solution for urban farmers who need substantial protection without a high cost or laborious construction.

E. Row Covers

The row cover is another form of wind barrier that has been used to protect crops. Row covers consist of light-permeable plastic sheets or fabrics that completely enclose crops. Thin polyethylene row covers are cheap and widely used, but are not helpful in addressing wind damage, as they are prone to tearing in strong wind. These thinner covers must be replaced every season and are generally used to combat pests (Kunicki et al., 1996; Good, 2012). Some other variants of row covers are constructed with thicker polypropylene plastic. Polypropylene covers do not easily tear, and stay grounded when anchored with sandbags or a dirt covering (Good, 2012). These covers will block wind effectively without being torn, and protect crops from harsh weather and pests. Polypropylene row covers are more expensive, but they have a service life of about four years (Kunicki, 1996; Good, 2012).

F. Greenhouses

Greenhouses are structures made with glass or polymer walls that completely enclose crops. As such, greenhouses completely protect crops from wind damage. This means that greenhouses are among the most effective wind barriers. However, greenhouses have disadvantages. Studies show that open-air rooftop farms are more efficient than rooftop greenhouses for crop production. The cost of tomato production in open-air rooftop gardens in Barcelona was shown to be 3.5 times less than in rooftop greenhouses (Sanyé-Mengual, 2015). However, greenhouses are not only more expensive to operate, they are also more expensive to construct than wind barriers, and require a significant amount of time to build. Greenhouse structures usually cost $25 per square foot, and establishing a greenhouse on a rooftop can cost upwards of $1,000,000 (Rifkin, 2011; Learn, n.d.). As such, greenhouses are not a viable solution, despite completely mitigating wind damage.

The research gathered in this literature review provides a foundation of information about effective wind barriers for ground-level rural farms. However, there is little to no published information about wind barriers for urban rooftop farms. More information is needed about rooftop wind dynamics and wind barriers designed for rooftop farms to develop an evidence-based recommendation to John Stoddard and other rooftop farmers.

METHODOLOGY

The goal of this project was to design wind barriers that provide effective protection for crops at Higher Ground Farm and other urban rooftop farms. To accomplish our goal, we have three objectives. Our first objective was to understand the unique conditions on rooftop farms that impact wind behavior and wind damage. Our second objective was to analyze existing ground-level wind barrier technology and modify it to meet the needs of our sponsor's farm and other rooftop farms. Our third objective is to further improve the wind barrier designs by creating and testing wind barrier prototypes. In order to meet our objectives, we conducted semi-structured interviews, a focus group, quantitative measurements, and qualitative observation. We used purposive and snowball sampling to identify interview participants. This project was granted WPI Institutional Review Board approval to conduct the interviews and focus group. All participants were informed of their right to anonymity.

I. UNDERSTAND UNIQUE CONDITIONS ON ROOFTOP FARMS THAT IMPACT WIND BEHAVIOR AND WIND DAMAGE

To meet the first objective, we met with our sponsor at his farm, collected wind data measurements at our sponsor's farm, conducted semi-structured interviews with urban rooftop farmers, and conducted a focus group with past Higher Ground Farm interns. The goal of the meeting with our sponsor was to gain an understanding of the layout of the farm, and to hear his thoughts and concerns about how wind was affecting his farm. The purpose of collecting wind data was to understand the unique environmental conditions on an urban rooftop farm. Wind velocity and direction measurements were taken with an anemometer to determine general wind patterns on the roof. These measurements also helped to determine the locations on the farm that are most affected by wind, as well as the differences between the roof's microclimate and the outside environment. This was accomplished by comparing local area wind data to the measurements collected at the farm.

Measurements were taken at six locations around the farm. The locations were chosen to provide a diverse sample of wind behavior data from all areas of the farm. *Figure 5* shows an overhead view of the farm layout with the six locations labelled. Locations 1 and 2 were placed in close proximity to the archway because John had theorized that the archway was funneling wind into the farm. Locations 3 and 4 were chosen to observe wind behavior near the parapet walls on the north and south ends of the farm. Locations 5 and 6 were chosen to observe wind behavior at the east end of the farm, farthest away from the archway. Measurements at all six locations on the Design Center roof were taken the same way: the anemometer was placed on top of the planter row, and wind speed measurements were recorded in a notebook at 30 second intervals for 15 minutes. Wind direction measurements were also recorded at 30 second intervals along with the speed measurements. The direction was determined with a homemade windsock fashioned from a trash bag, a reshaped coat hanger, and tape. Using a smartphone compass, long metal pipes were placed on the ground to indicate the cardinal directions. These markers were visually compared to the windsock to determine the current wind direction for every speed measurement.

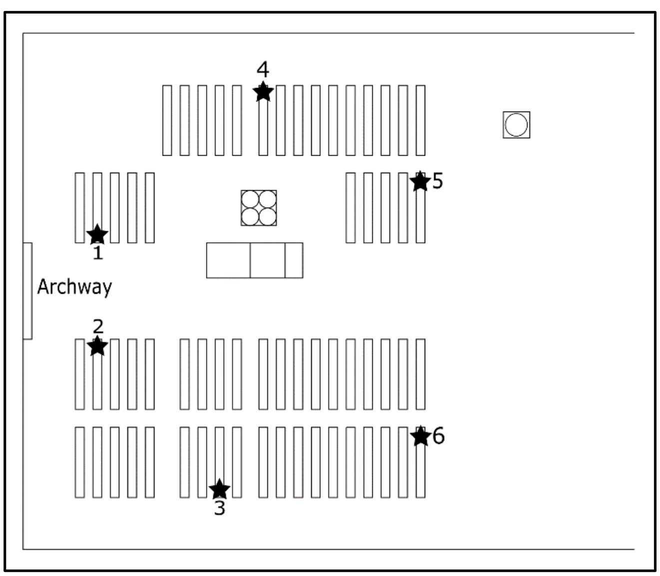


***Figure 5:* Measurement Locations**

Semi-structured interviews with other urban rooftop farmers and a focus group of farm interns were conducted to gain additional perspectives on wind damage to crops and space constraints on rooftop farms. Appendices A, B, and C contain the guide sheets that were used for the interviews and focus group.

II. Analyze Existing Ground-Level Wind Barrier Technology and Modify it to Meet the Needs of our Sponsor's Farm and Other Rooftop Farms

To meet the second objective, we analyzed secondary data, conducted semi-structured interviews with urban rooftop farmers and wind barrier experts, and conducted a focus group with past Higher Ground Farm interns. Secondary data found in the literature review of this report provided information about effective ground-level wind barriers. These barrier designs and their properties were modified to be effective on rooftops based on the information gathered for the first objective. The goal of the interviews with other rooftop farmers was to learn how wind impacts their farms, and what measures each farm has taken to protect their crops from wind damage. This information allowed our barrier designs to be tailored not only for Higher Ground Farm, but for future application on other rooftop farms. It also ensured that no effective barrier designs that have been successfully employed were overlooked. The goal of the interviews with wind barrier experts was to receive feedback on the barrier designs and our plans for prototype testing. Their feedback improved the designs by pointing out flaws and suggesting solutions to those flaws. Their feedback also ensured that there weren't any barrier designs or barrier technologies that were overlooked. Appendices A and B contain the guide sheets that were used for these interviews. Perspectives about the barrier designs were also gathered from a focus group of Higher Ground Farm volunteers. The purpose of the focus group was to gain an understanding of how each barrier may impact work flow on the farm. At the conclusion of the focus group, our goal was to have an understanding of which barriers would impede farm work the most, and have suggestions on how to improve them. Appendix C contains the guideline sheet that was used for the focus group.

III. Further Improve the Wind Barrier Designs by Creating and Testing Wind Barrier Prototypes

To meet the third objective, we created wind barrier prototypes and gathered quantitative wind measurements and qualitative observations. Testing was performed to evaluate barrier durability and effectiveness, and to reveal design flaws that were not previously considered. This testing was performed on the top level of the six-story tall WPI-owned Gateway parking garage. Prototype barriers were created and tested for two designs, ivy walls and row covers. We did not test the grass barriers because we did not have time to grow the grass for them, and we eventually removed them from our recommendations to John Stoddard due to space constraints on his farm.

The testing of the ivy wall barriers was focused on the durability of the structures under heavy wind conditions, and their effectiveness as wind barriers. First, normal conditions were simulated. Fake ivy was attached to the lattices of four prototype ivy wall structures. These structures were arranged in a square surrounding an anemometer, and a second anemometer was placed outside the barrier enclosure. Wind speeds were measured inside and outside the barrier enclosure every 30 seconds. These measurements were taken for fifteen minutes each day over four days. The measurement values were then compared to show that the design adequately reduces wind speed. We also performed a "worst case scenario" test. This test involved covering the entire lattice of the ivy wall with a plastic sheet to minimize the porosity, which maximized the force applied to the face of the lattice structure. This test ensured that the design remains standing and structurally sound during harsh conditions.

The testing for the row cover design was focused more on the functionality of the securing mechanism than on their effectiveness. Row covers completely surround crops with plastic, so crops are fully protected from wind. However, the durability and stability of the row covers needed to be tested. A hook system was developed using carabiners to secure the row covers from strong winds while simultaneously allowing workers to easily access covered crops. Both facets of the hook system required testing. The row cover prototype was assembled at the testing location, and three distinct tests were performed. The first test involved securing the row covers over milk crates using the hook system and leaving them there for several hours. During this period, the covers were inspected for damage, and observed to monitor how they responded to wind gusts. After this period, the second test was performed. This involved opening the row covers in windy conditions to evaluate how quickly and easily the covers could be transitioned from "closed" to "open". The purpose of this test was to simulate farmers opening the covers to work on crops, and to find out how disruptive this process was. The third test involved leaving the row covers secured "open" for several hours. During this time period, the covers were observed to evaluate whether the securing mechanism kept the covers from flapping too violently in the wind. All three of these tests addressed the concerns of wind barrier experts and Higher Ground Farm volunteers.

RESULTS

This section contains all the information that was gathered to meet the project objectives. This information is organized into three sections, with each section containing all the results that were collected to satisfy a project objective. The summation of the data reported in this section is used as the basis for the design recommendations to John Stoddard.

I. RESULTS: UNDERSTAND UNIQUE CONDITIONS ON ROOFTOP FARMS THAT IMPACT WIND BEHAVIOR AND WIND DAMAGE

This section contains the results of all research conducted to meet the first project objective. The data included was obtained from wind speed measurements taken on Higher Ground Farm, as well as interviews with other rooftop farmers about their experiences with wind damage.

We visited Higher Ground Farm for the first time on October 15th, 2016. This visit allowed us to see the farm's layout in person. We kept the size and orientation of the farm layout in mind when designing barriers so that they would not disrupt farm work. We also observed the planter setup at Higher Ground Farm for the first time. Higher Ground Farm uses rows of milk crates filled with soil as planters (*Figure 6*). We also discussed details of the project with Stoddard, and he provided us with information about the wind situation. Stoddard hypothesized that the large archway next to the crops was likely funneling wind into the center of the farm area (*Figure 7*). Additionally, Stoddard stated that his tomato plants were experiencing the most damage due to their height.

***Figure 6*: Milk Crate Planter Rows**

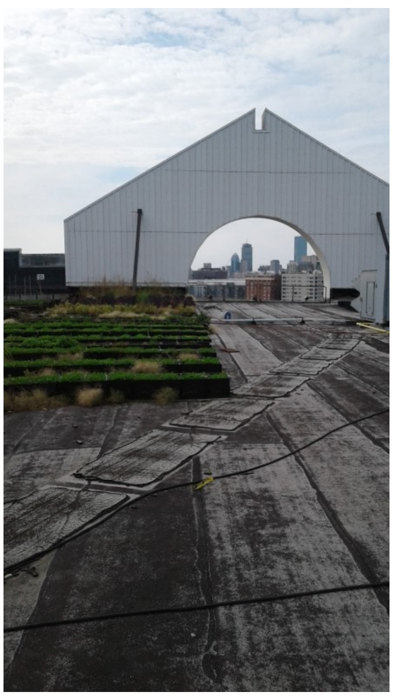


***Figure 7*: HGF Archway**

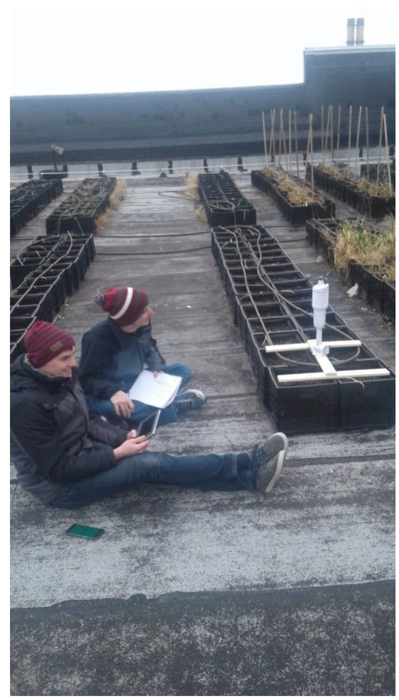


***Figure 8*: Wind Measurements**

We also interviewed two urban rooftop farmers. We interviewed Arlene Throness of Ryerson Urban Farm on January 20th, 2017. Ryerson Urban Farm is located at Ryerson University in Ontario, Canada. Arlene informed us that during the 2016 growing season, their tomato plants had experienced some mild wind damage. Wind caused increased rigidity in the tomato plants stalks, and this lead to many of the stalks snapping. This was the first instance of wind damage that Ryerson Urban Farm had experienced, and so at the time we talked to Arlene, the farm had not implemented any type of wind shielding (A. Throness, Phone interview, 2017). This information was evidence that farms besides Higher Ground Farm experience crop damage caused by wind. We then interviewed Tiffany Henkel of Hell's Kitchen Farm Project (HKFP) on February 23rd, 2017. HKFP is located on the roof of the Metro Baptist Church building. The church is five stories tall, and the west side of the rooftop is exposed to winds from the Hudson River. The farm plants their crops in four-foot diameter kiddie pools filled with dirt. Henkel stated that wind is a nuisance on the farm, and that loose items like chairs have to be secured down. However, she said that wind hadn't been enough of an issue to warrant using wind barriers. According to Henkel, the four-foot concrete parapet wall that surrounds the roof provides adequate protection (T. Henkel, Phone interview, 2017). She mentioned that there is a two-foot metal railing attached to the top the parapet wall. This railing likely reduces turbulent winds on the farm by disrupting wind shear off the top of the parapet. Despite the fact that the crops at HKFP have not experienced wind damage, wind has still caused other problems on the farm, and wind might be a larger issue if their parapet wall did not have a metal railing to break up wind shear.

Wind speed measurements were taken on Higher Ground Farm to gain a better understanding of the conditions at the farm (*Figure 8*). The team travelled to the Boston Design Center on January 22nd, 2017. Measurements were taken at six locations between 14:00 and 16:00. A LaCrosse Technology 327-1414W Color Wireless Wind Speed Weather Station was used to take these measurements. Local wind data during this period was found on the National Oceanic and Atmospheric Administration's online Quality-Controlled Climatological Database. According to their measurements taken at Logan Airport (roughly 2 miles from Higher Ground

Farm), the average wind speed between 14:00 and 16:00 was 17 mph, with wind blowing from NE to SW. This data can be seen in its original form in *Table 1*.

1/31/2017 QUALITY CONTROLLED Local Climatological Data: GEN E L LOGAN INTERNATIONAL AIRPORT

U.S. Department of Commerce
National Oceanic & Atmospheric Administration

QUALITY CONTROLLED LOCAL CLIMATOLOGICAL DATA
(final)
HOURLY OBSERVATIONS TABLE
GEN E L LOGAN INTERNATIONAL AIRPORT
(14739)
BOSTON, MA
(01/2017)

National Climatic Data Center
Federal Building
151 Patton Avenue
Asheville, North Carolina 28801

Elevation: 12 ft. above sea level
Latitude: 42.360
Longitude: -71.009
Data Version: VER3

Date	Time (LST)	Station Type	Sky Conditions	Visibility (SM)	Weather Type	Dry Bulb Temp (F)	Dry Bulb Temp (C)	Wet Bulb Temp (F)	Wet Bulb Temp (C)	Dew Point Temp (F)	Dew Point Temp (C)	Rel Humd %	Wind Speed (MPH)	Wind Dir	Wind Gusts (MPH)	Station Pressure (in. hg)	Press Tend	Net 3-hr Chg (mb)	Sea Level Pressure (in. hg)	Report Type	Precip. Total (in)	Alti-meter (in. hg)
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
22	0054	11	FEW250	9.00		40	4.4	39	3.9	38	3.3	93	0	000		29.72			29.75	AA		29.75
22	0154	11	BKN220	7.00		40	4.4	40	4.4	40	4.4	100	3	190		29.72			29.75	AA		29.75
22	0254	11	OVC200	6.00	BR	41	5.0	41	4.7	40	4.4	96	0	000		29.72			29.75	AA		29.75
22	0354	11	OVC190	6.00	BR	40	4.4	40	4.4	40	4.4	100	3	180		29.72			29.74	AA		29.75
22	0454	11	OVC190	6.00	BR	39	3.9	39	3.8	39	3.9	100	5	180		29.72			29.74	AA		29.75
22	0554	11	FEW040 SCT140 BKN220	6.00	BR	39	3.9	39	3.6	38	3.3	96	0	000		29.74			29.77	AA		29.77
22	0654	11	FEW040 BKN080 BKN220	9.00		42	5.6	42	5.3	41	5.0	96	5	330		29.76			29.78	AA		29.79
22	0754	11	BKN090 BKN250	10.00		44	6.7	43	5.8	41	5.0	89	3	020		29.76			29.79	AA		29.79
22	0854	11	BKN090 BKN250	8.00		43	6.1	43	5.8	42	5.6	96	0	000		29.78			29.80	AA		29.81
22	0954	11	BKN090 BKN250	10.00		44	6.7	42	5.6	40	4.4	86	7	030		29.79			29.82	AA		29.82
22	1054	11	BKN090 BKN250	10.00		46	7.8	44	6.7	42	5.6	86	11	030		29.79			29.81	AA		29.82
22	1150	11	BKN011 OVC090	10.00		46	8.0	45	6.9	43	6.0	89	13	030		29.78			M	SP		29.81
22	1154	11	BKN011 OVC090	10.00		47	8.3	45	7.0	42	5.6	83	14	040		29.78			29.80	AA		29.81
22	1249	11	SCT010 BKN029 OVC100	10.00		46	8.0	45	6.9	43	6.0	89	15	050		29.79			M	SP		29.82
22	1254	11	SCT010 BKN029 OVC100	10.00		46	7.8	44	6.7	42	5.6	86	14	050		29.80			29.82	AA		29.83
22	1354	11	FEW010 OVC024	10.00		44	6.7	43	6.1	42	5.6	93	16	040		29.79			29.82	AA		29.82
22	1356	11	SCT008 OVC015	10.00		44	6.7	43	6.1	42	5.6	93	15	040		29.79			M	SP		29.82
22	1402	11	SCT008 OVC015	2.50	BR	44	6.7	43	6.1	42	5.6	93	18	040		29.79			M	SP		29.82
22	1404	11	BKN006 OVC015	2.50	BR	44	6.7	43	6.1	42	5.6	93	18	040		29.79			M	SP		29.82
22	1413	11	BKN006 OVC015	1.75	-RA BR	43	6.1	43	5.8	42	5.6	96	20	030		29.79			M	SP		29.82
22	1454	11	OVC005	1.50	-RA BR	42	5.6	42	5.5	42	5.6	100	15	050		29.82			29.84	AA	T	29.85
22	1554	11	OVC005	1.50	-RA BR	41	5.0	41	5.0	41	5.0	100	17	050		29.83			29.86	AA	0.03	29.86
22	1654	11	FEW004 OVC005	1.50	-RA BR	41	5.0	41	4.7	40	4.4	96	17	050		29.84			29.87	AA	0.01	29.87
22	1747	11	OVC010	1.50	-RA BR	41	5.0	41	4.7	40	4.4	96	18	050		29.86			M	SP		29.89
22	1752	11	OVC008	1.50	-RA BR	39	4.0	39	3.8	39	4.0	100	18	060		29.86			M	SP		29.89
22	1754	11	OVC008	1.50	-RA BR	40	4.4	40	4.4	40	4.4	100	20	060		29.87			29.89	AA	T	29.90
22	1821	11	OVC012	1.50	-RA	40	4.4	40	4.1	39	3.9	96	16	060		29.90			M	SP		29.93
22	1854	11	OVC013	1.50	-RA	40	4.4	39	3.9	38	3.3	93	20	060		29.90			29.93	AA	T	29.93
22	1929	11	OVC014	10.00		40	4.4	39	3.9	38	3.3	93	18	060		29.89			M	SP		29.92
22	1941	11	OVC015	10.00		40	4.4	39	3.9	38	3.3	93	20	060		29.89			M	SP		29.92
22	1954	11	OVC015	10.00		40	4.4	39	3.9	38	3.3	93	17	060	25	29.90			29.92	AA	T	29.93
22	2054	11	OVC018	10.00		41	5.0	39	4.0	37	2.8	86	17	060		29.93			29.96	AA		29.96
22	2154	11	OVC021	10.00		41	5.0	39	4.0	37	2.8	86	18	060		29.93			29.96	AA		29.96
22	2254	11	FEW014 OVC021	4.00	-RA BR	39	3.9	38	3.1	36	2.2	89	22	060		29.95			29.98	AA	0.02	29.98
22	2338	11	SCT022 OVC030	10.00	-RA	40	4.4	38	3.2	35	1.7	82	21	060		29.94			M	SP		29.97
22	2352	11	BKN025 OVC030	10.00		39	4.0	38	3.1	36	2.0	89	17	060		29.94			M	SP		29.97
22	2354	11	BKN025 OVC030	10.00		40	4.4	38	3.2	35	1.7	82	20	060		29.94			29.97	AA	T	29.97

Table 1: **Original NOAA Quality Controlled Climatological Data ("QUALITY", 2017)**

After transferring the collected data to a spreadsheet (*Appendix F, Table 7)*, it was used to create a graphic, seen in *Figure 5*. The graphic shows an arrow at each of the six measurement locations, with each arrow showing the average speed and wind direction of the measurements for that location. The wind direction measurements were averaged using a representative coordinate system. North and South were represented by the positive and negative y-axis, respectively; East and West were represented by the positive and negative x-axis, respectively. The quantity of each four direction measurements were tallied up, and then these four totals were treated as vectors. In the case of diagonal measurements (NE, NW, SE, SW), they were treated as a 45°-45°-90° triangle with hypotenuse length 1. The side lengths of this triangle (0.71) were then added to their respective cardinal direction totals. For example, a NW measurement would contribute 0.71 to the North total, and 0.71 to the West total. After the four cardinal totals were compiled, they were refined into a vertical (N/S) and horizontal (E/W) vector by adding the positive and negative totals for each axis of the coordinate system. For example, if there were three North measurements and one South measurement, the resulting average direction would be 2 North. The resulting horizontal and vertical vectors were then summed using vector addition to arrive at a final wind direction vector.

The numbers displayed by each arrow in *Figure 5* represent the location number. Blue arrows represent wind behavior within the microclimate of the rooftop. The red arrow represents wind behavior in the greater region outside the farm. The shapes outlined in black represent the rows of planters, as well as other miscellaneous structures on the roof. Google Maps was referenced while creating the graphic to ensure that the shape and size of these structures, as well as the distances between them and the borders of the roof, are to scale. Arrow length in *Figure 9* indicates average wind speed, meaning that the longer the arrow, the higher the average wind speed at that location. Included below *Figure 9* is a chart (*Table 2)* showing the numerical average wind speed values at each location.

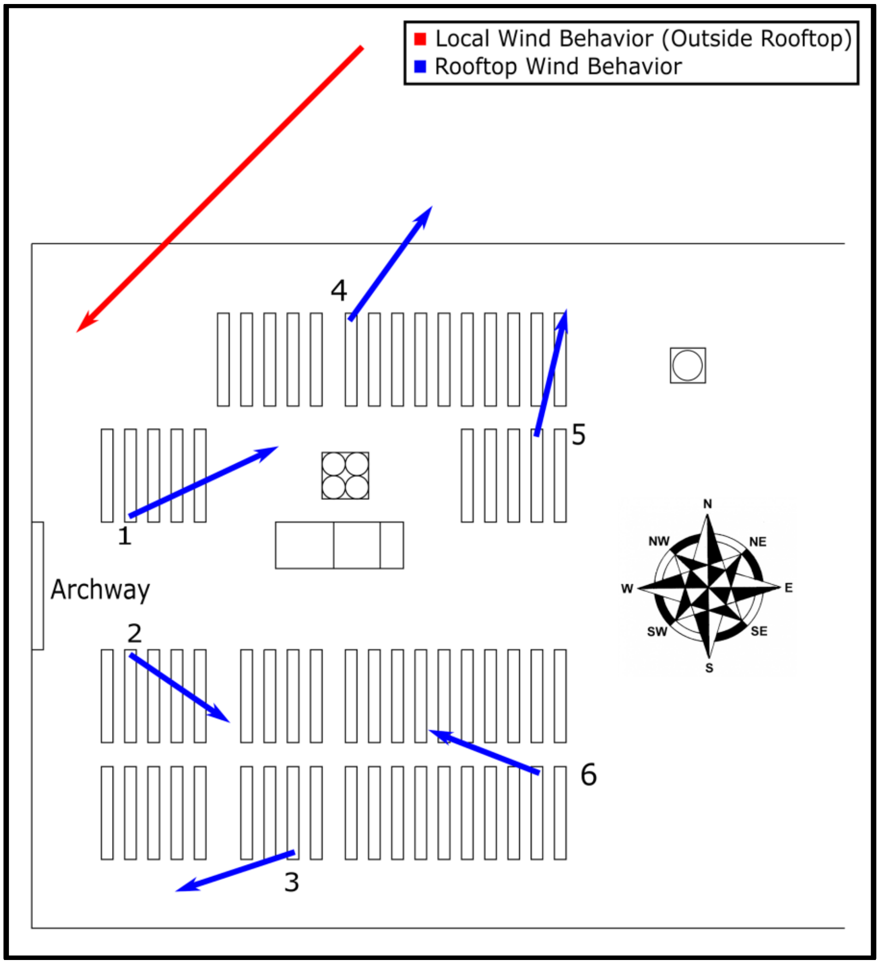


Figure 9: **On Site Wind Measurement Graphic**

Location:	1	2	3	4	5	6
Average Speed (mph):	6.5	4.9	4.9	5.7	5.2	4.7

Table 2: **On Site Wind Measurement Average Speeds**

Interpretations about general wind patterns on the farm can be made from this data. The wind data we collected is not statistically significant. Therefore, the interpretations can be understood as informed estimates based on our data-driven knowledge of how physical objects alter wind behavior.

Locations 1 and 2 were closest to the archway. The average wind directions at these locations were pointed away from the archway. This indicates one of two things. External wind is being funneled through the archway opening onto the rooftop, or external wind passing over the parapet wall is deflecting off the archway wall and back onto the rooftop. Both of these possibilities indicate that wind near the archway will typically flow away from the archway. Locations 4 and 5 on the north side of the farm had average directions that were similar to the direction at location 2. This shows that wind on the north side of the farm generally continued to travel outward from the archway without changing direction.

The south side of the farm did not experience the same trend. The average wind directions at locations 3 and 6 were not continuous with location 1. They are generally oriented towards the archway, not away from it. This difference in direction trends between the north and south sides of the farm may be attributable to the parapet wall. Given that external wind was moving southwest, the north side of the farm was within the protected region of the parapet wall. This prevented external wind from influencing the direction of wind flow in this region or from causing excessive turbulence. Conversely, the south side of the farm was outside of the protected region. In this area, turbulence caused by wind shear off the top of the parapet wall interacts with the wind flow from the archway. This explains the lack of a wind direction trend in the southern half of the farm. This also explains why the directions at locations 4 and 5 are angled slightly northward, towards the parapet wall. The protected region created by the wall will have a lower air pressure than other areas. This low pressure region will draw air flow towards the parapet wall.

The result of these interpretations is that in most cases, one half of the farm will experience winds moving in a somewhat uniform direction, whereas the other half will experience turbulent winds with no uniform direction. This indicates that wind barriers must provide complete 360-degree coverage to be effective. The regions of the farm experiencing turbulent wind will change constantly depending on the prevailing direction of external winds.

II. Results: Analyze Existing Ground-Level Wind Barrier Technology and Modify it to Meet the Needs of our Sponsor's Farm and Other Rooftop Farms

This section contains all research conducted to meet the second project objective. Initial barrier designs were informed by research from the literature review. After developing initial designs, the designs and testing plans were modified based on feedback from former Higher Ground Farm workers, other rooftop farmers, and wind barrier experts. These modifications focused on increasing the effectiveness and durability of the designs, and avoiding negative impacts to farm work.

A. *Initial Barrier Designs*

Research from the literature review showed that porous wind barriers are more effective, as they significantly reduce downwind turbulence. Organic barriers are especially effective due to their large surface area, variable porosity, and flexibility compared to wall-type barriers. Non-porous wall-type barriers were eliminated early in the design process because of their tendency to create large regions of downwind turbulence.

Three initial barrier designs were developed. The first design was a wheatgrass barrier. This organic barrier design was inspired by the study of tall wheatgrass found in Brandle's 2012 book "Windbreak Technology". The first iteration of this design consisted of a large constructed wooden planter box, filled with soil and seeded with Rush wheatgrass (*Thinopyrum intermedium*). *Figure 10* contains a drawing of this design.

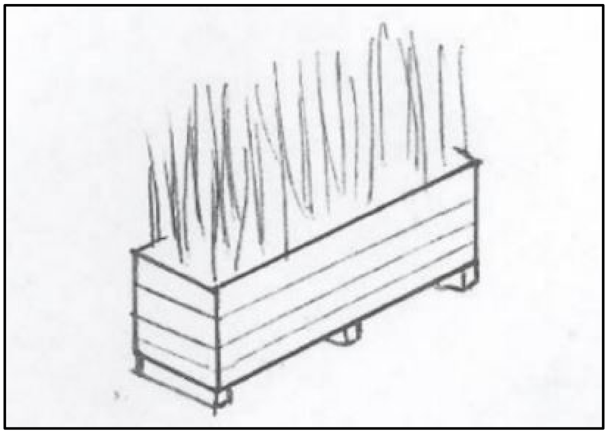


***Figure 10:* Initial Grass Barrier Design (David Frederick)**

Rush wheatgrass is a tall grass, introduced to the United States in 1962. It has been successfully cultivated throughout the Midwest and Northwest United States, and is adapted to cool, wet climates (Rush, 2013). Rush wheatgrass was chosen for the barrier because of its seed vigor (germination performance), height (three to four feet), fast emergence, and strong growth throughout spring, summer, and fall (Rush, 2013).

The second initial design was a modified row cover design. We chose this design because of its simplicity and low cost. Additionally, this design provided complete coverage for crops from all wind directions. The design consisted of metal hoops placed along planter rows to hold up the row cover plastic. In this design, each row cover had five hoops, and each end of the hoops was placed one-foot deep into the soil. The row cover fabric was cut to size, draped over the hoops, and secured on one side of the rows by tucking a foot of the fabric end under the milk crate rows. The other side of the fabric was secured to the crates with carabiners attached to the fabric end. This was designed to give farm workers easy access to the rows by detaching the carabiners from the crates and pulling the row cover back. Six carabiners were used for each row, and each hole in the row cover fabric was protected with grommets. *Figure 11* shows a simple drawing of row covers on the planter rows, not to scale.

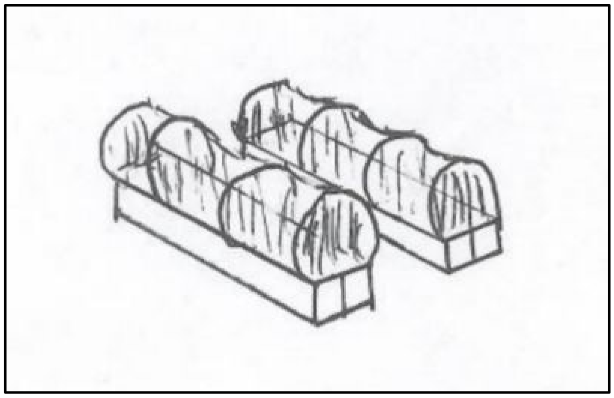


Figure 11: **Initial Row Cover Design (D. Frederick)**

The third initial design was a lattice wall covered with ivy. This design combined the positive effects of porous wall-type barriers and organic barriers. It was designed specifically to protect the tomato plants on Stoddard's farm, since they were too tall to protect with grass barriers or row covers.

The initial ivy wall design consisted of a wooden lattice attached to the front of a wooden frame. The vertical sides of the frame extended down to form legs that were attached to triangular supports. These supports were attached to a wooden base designed to hold three milk crates. These milk crates would be filled with dirt and a Boston ivy plant would be seeded in the center milk crate. As the ivy grew, it would attach to and climb up the lattice, providing flexible leaves to block wind coming through the lattice. Boston ivy was chosen over other ivy varieties for several reasons. It is a very fast-growing and tough plant, and has been shown to grow well in a wide variety of urban conditions such as heat, drought, restricted root zones, and heavy pruning (Rhodus, n.d.). Boston ivy also has a unique mechanism for attaching itself to structures. Unlike other ivies that burrow their shoots into the surface of the structure, Boston ivy tendrils have sticky discs that latch onto surfaces (Boston, n.d.). This means that Boston ivy does not physically damage the structures that it climbs. *Figure 12* shows a drawing of the initial ivy wall design without ivy.

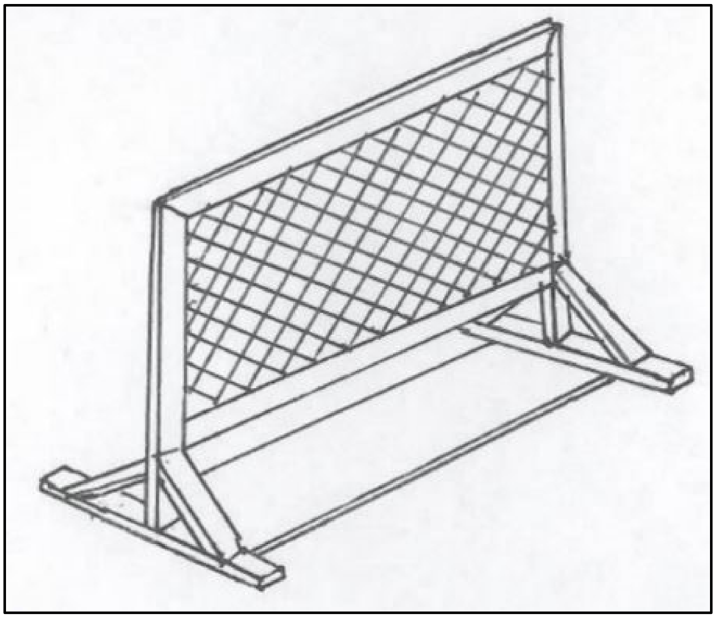


Figure 12: **Initial Ivy Wall Design (D. Frederick)**

B. Grass Barrier Design

Prior to the focus group and barrier expert interviews, the grass barrier design was modified. The container for the grass design was changed from a constructed wooden box to a milk crate. This had multiple benefits. The barrier cost was reduced, and the container no longer required assembly. The individual units of the new design also weighed significantly less, increasing maneuverability. Additionally, since the crops at Higher Ground Farm are planted in milk crates, the grass would be at an optimal height to block wind. A drawing of this updated design is shown in *Figure 13*.

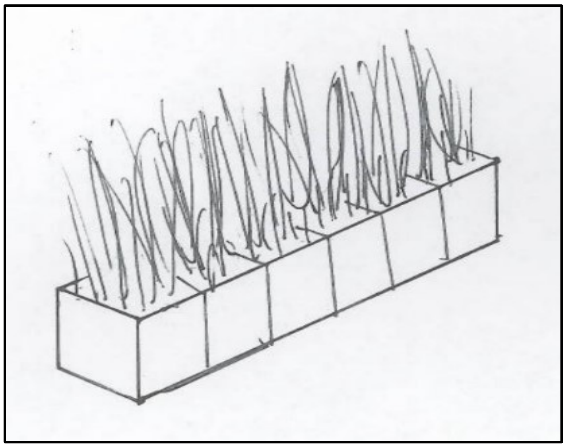


Figure 13: **Updated Grass Barrier (D. Frederick)**

Dr. James Brandle is a professor at the University of Nebraska-Lincoln and the primary author of the 2012 book “Windbreak Technology”, which is referenced extensively in the literature review. Dr. Brandle’s areas of focus are windbreaks and ecology. Brandle has also done work with shelterbelts, forestry, and sustainable agriculture. He thought that the grass barrier would be effective. He noted that wheatgrass wind barriers are common in the wheat production industry in Wyoming and Montana (J. Brandle, Phone interview, 2017). There are also locations in the Canadian Prairies that use wheatgrass as a wind barrier. The fact that an industry already employs tall grasses as wind barriers strongly indicates that it is an effective solution. Tiffany Henkel, an executive director and pastor at Metro Baptist Church in Hell’s Kitchen, NY, has visited two other rooftop farms in Brooklyn, NY. She noticed that both of these farms had a perimeter of shrubs around their roofs, even though these locations were less exposed than the roof of the Metro Baptist Church. Both of these locations had parapet walls, but the shrubs at both farms grew higher than the walls. These shrubs were likely planted as wind barriers, given their placement and the lack of other non-food producing plants at these farms. This also supports the effectiveness of the grass barrier.

Dr. Richard Sutton, another professor at the University of Nebraska-Lincoln who specializes in ecology and green roofs, also thought the grass barriers would be effective. He mentioned that they would be better suited for protecting shorter plants, and that the ivy walls are best suited to protect the tomato plants (R. Sutton, Phone interview, 2017). This observation was in line with our plan to use the ivy walls only to protect the tomato plants.

The focus group, consisting of four former Higher Ground Farm interns, was generally positive about the grass barriers. Their primary concern with this barrier design was seed production. Several participants were worried that seeds from the grass would spread to the planter rows and become a weed that competed with crops for space and nutrients. This concern was addressed after the interview with Dr. Sutton, when he suggested using little bluestem instead of rush wheatgrass. Little bluestem is a grass native to the Northeast United States that grows to roughly the same height as Rush wheatgrass, but has increased stalk durability and reduced seed vigor compared to Rush (Little, 2002; Rush, 2013). This means that it does not germinate well when there is competition for nutrients from other plants. Thus, if little bluestem seeds were to migrate to planter rows, they would not likely sprout given the nutrient competition from established crops.

C. Row Cover Design

The interviews and focus group showed that the row cover design has several strengths. In his interview, Dr. Brandle stated that the row covers would likely provide the greatest level of wind reduction (Brandle, Phone interview, 2017). Additionally, the focus group was positive about how little space the row covers would take up compared to the other barrier designs. They also mentioned that the row covers could be useful for pest management. Tiffany Henkel said that the HKFP team has considered using row covers in the past, but they've refrained because they don't have a reliable method to secure them down (T. Henkel, Phone interview, 2017). This implies that Henkel would consider implementing our row cover design since it addresses this concern.

The focus group was more concerned about row covers compared to the other designs. In the past, the farm used row covers made from a gauze-like material for germinating seeds. These row covers were held down with clasps, and when they were opened to access the rows, the covers would frequently flap in the wind. The group agreed that the flapping row covers were a hindrance to their work. Testing of the hook system for securing the polypropylene row covers was added to the prototype testing plan to account for this observation. This ensured that the recommended row cover implementation would not have a flapping problem. Row cover testing plans were also altered to include measurements of the temperature difference inside and outside the row covers.

Dr. Sutton warned us that if wind gets under any stray piece of row cover fabric, it will start flapping around violently and be difficult to control (Sutton, Phone interview, 2017). To mitigate this risk, he suggested making sure that both ends of the row covers are held down with plenty of weight. He mentioned the Venturi Principle, and how it will apply to the row covers given the difference in air pressure between the inside and outside of the covers.

D. Ivy Wall Design

Russ Lang, a materials and structures lab manager at Worcester Polytechnic Institute with 15 years of manufacturing engineering experience, evaluated the ivy wall design early in the project. When we expressed that we wanted the design to be cheaper and easier to assemble, Lang suggested a couple of improvements. First, he suggested using wingnuts to attach the triangular supports and base plate to the lattice frame. This would make it simple and easy to disassemble the barrier into two parts. Lang also suggested that the base plate and triangular supports should be wider, to give the design stronger support and allow for more milk crates on the other side of the lattice if more weight was needed. A drawing of this updated design can be seen in *Figure 14*.

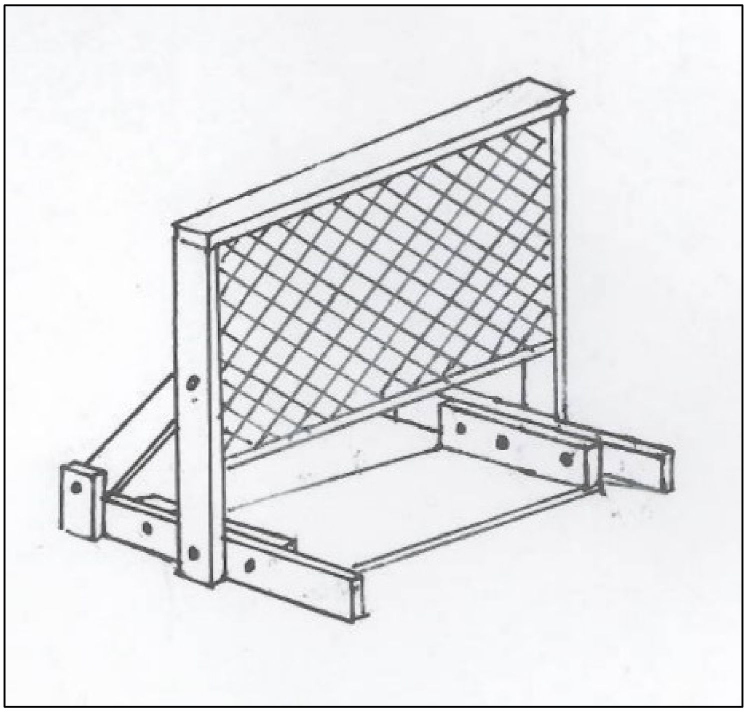


Figure 14: **Updated Ivy Wall Design**

Brandle stated that the ivy wall design was most similar to a traditional windbreak. In general, traditional porous windbreaks have a narrow protected zone, usually no more than ten times the height of the barrier. Interestingly, the size of the protected zone can be manipulated by altering the density of the ivy in this design. Overall, Brandle thought that the ivy wall design was very intriguing due to the potential for dynamic density of organic material. He also thought that this design would effectively avoid causing turbulence compared to solid wall-type barriers, and that this barrier would allow for a more optimized density and porosity compared to wheatgrass barriers.

When discussing ivy walls, the focus group consensus was that they were not large enough to physically impede work. After viewing an animation of a SolidWorks model of the ivy wall, the participants also stated that they would not have difficulty assembling a barrier if given the parts to do so. They suggested creating an infographic or guide for assembling the ivy walls. In response to this, a user manual was created and included in our recommendations.

Dr. Sutton had several thoughts and concerns about the ivy wall structure that lead to modifications. He expressed concern about the load that wind would place on the ivy walls. He also suggested testing the barrier in high-speed wind conditions to ensure that it could withstand the conditions on the roof. This concern was addressed in our testing protocol by testing the ivy wall prototype on the roof of Gateway Garage. He also cautioned us to make sure that the ivy walls could be disassembled, so that they could be deconstructed and set aside in the winter to avoid undue stress from winter storms. Disassembly of the ivy wall design is simple, only requiring removal of the wing nuts that attach the diagonal supports to the frame. Dr. Sutton also stated that while Boston Ivy is a tough plant, the maturity of the ivy plant when it is placed in the barrier will affect its growth rate. He stated that a gallon-sized, established ivy plant will likely be unaffected by the harsher conditions on the rooftop, whereas planting seeds or a young plant in a harsh environment may stunt its growth. As such, we included this in our recommendation.

III. Results: Further Improve the Wind Barrier Designs by Creating and Testing Wind Barrier Prototypes

This section contains all the data that was collected to meet the third project objective. This information was obtained from wind speed measurements taken at the top of the Gateway parking garage, as well as from qualitative observations of wind barrier prototypes.

A. Ivy Wall Testing

Effectiveness testing and stability testing were conducted with prototype ivy wall barriers, as described in the methodology (*Figure 16*). Wind speed measurements for the effectiveness testing were taken on four separate days between April 10th and April 15th, 2017. Two anemometers were used, both of the same make and model as the anemometer used for the wind measurements at Higher Ground Farm. One anemometer was placed on top of a milk crate inside an enclosure of four ivy wall prototypes, and the second anemometer was placed on a milk crate roughly 190 feet away at the other end of the parking garage. Ideally, the second anemometer would have been placed right outside the barrier enclosure, but we discovered that both digital displays would pick up the same signal from one anemometer if they were placed any closer together. The "current wind speed" measurement displayed by the anemometers is actually an average of the most recent 30 seconds of measurements taken by the device. It was not possible for us to know if this 30 second window was synced between the two anemometers; if it was not, then the current speed measurements would be averages from slightly different time intervals. This fact, combined with the distance between the anemometers which allowed the wind behavior to change slightly, means that individual measurements from the anemometers taken at the same time cannot be compared to each other. However, when taking measurements over a longer period of time, these inaccuracies do not significantly impact the average results.

Thus, we can compare the average wind speed inside and outside the barrier enclosure on each day of testing to get an estimation of how much the ivy wall barriers reduce wind speed. A table of the individual measurements gathered during this testing can be found in Table X in Appendix X. *Figure 15* contains a bar graph comparing the average wind speeds inside and outside the barriers for each day of testing. The numbers above each bar indicate the numerical average wind speed for that data set.

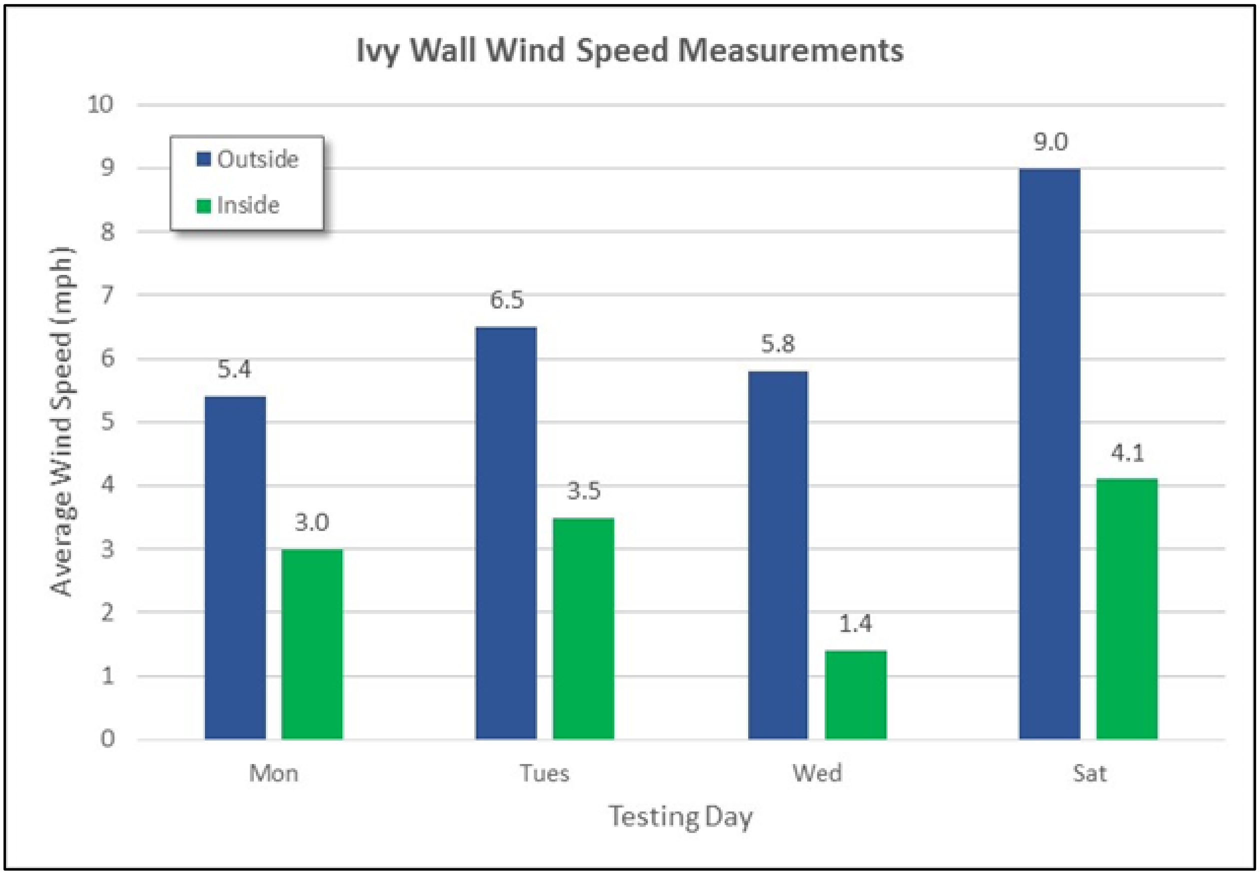


Figure 15: **Average Ivy Wall Testing Wind Speeds**

To interpret this data, we calculated the average amount that the ivy walls reduced wind speed as a percentage. First, the percent reduction for each day of testing was calculated by applying the formula

$$r = \left(1 - \frac{s_i}{s_o}\right) * 100$$

where r is the percent reduction, s_i is the average wind speed inside the barriers, and s_o is the average wind speed outside the barrier. The percent reductions from the four days of testing were then averaged together to find the average wind speed reduction percentage caused by the ivy walls. The results of these calculations can be found in *Table 3* below.

	Monday	Tuesday	Wednesday	Saturday	**Average**
% Reduction	43.63%	46.24%	76.55%	54.52%	**55.23%**

***Table 3*: Ivy Wall Wind Speed Reduction Percentage**

The major conclusion of this testing was that the ivy walls reduced wind speeds by an average of 55%. This proved that the ivy walls would effectively protect crops from harsh winds.

The ivy wall stability test was conducted over four days (April 24th to April 27th, 2017) by leaving an ivy wall at the testing site with a plastic sheet attached to the lattice face for four days (*Figure 17*). The barrier was held down by 200 lbs of sandbags placed on the baseplate. This weight in soil would fill the three milk crates intended to hold the ivy plant. Throughout the four-day testing period, we checked on the barrier once per day to inspect it for physical damage or deformation. During periods of observation, the barrier was stable and remained grounded, and after the testing period, the barrier had not sustained any physical damage. This was confirmed by disassembling the barrier so that each part could be felt for weakness or damage that was not visibly apparent. Online wind speed measurements from the four-day testing period were consulted to understand the conditions that the barrier was tested in. Data from Worcester Regional Airport (~ 4 miles from Gateway garage), found at wunderground.com, revealed that the largest wind speed recorded during the testing period was 29 mph ("Weather History", n.d.). A chart with the average wind speeds, maximum wind speeds, and maximum gust speeds from the four testing days can be found below in *Table 4.*

	April 24	April 25	April 26	April 27
Average Wind Speed	8 mph	12 mph	9 mph	5 mph
Maximum Wind Speed	18 mph	17 mph	16 mph	14 mph
Maximum Gust Speed	22 mph	29 mph	23 mph	19 mph

***Table 4:* Worcester Regional Airport Wind Speed Data**

The average wind speeds on all days except April 27th were higher than the largest average wind speed that we measured at Higher Ground Farm (6.5 mph), and the maximum speeds and maximum gusts from all four days far exceeded the average wind speeds measured at Higher Ground Farm. Based on this, we can conclude that the ivy wall barrier is strong enough to withstand the conditions on Higher Ground Farm and other rooftop farms, even if the ivy becomes very thick due to infrequent trimming by farmers.

Figure 16: **Wind Speed Reduction Testing**

Figure 17: **Stability Testing**

B. Row Cover Testing

Functionality testing of the carabiner attachment mechanism was conducted with a small section of row covers, as described in the methodology. Two rows of four milk crates were used to simulate a small section of the planter rows at Higher Ground Farm. Four 50 lb sandbags were used to weigh down the row covers in place of soil, one in each of the four milk crates at the end of the row. The milk crates were then zip-tied together to ensure that they stayed in place. One metal hoop was placed at each end of the milk crate row. Polypropylene fabric with 70% light permeability, ½" grommets, and 1" carabiners were used when setting up the row covers. A grommet tool kit was used to attach the grommets to the row cover fabric.

The row covers were first tested while in the "closed" position (*Figure 18*). Observation revealed that the carabiner attachment mechanism kept the row cover fabric secure, and allowed the covers to be held under slight tension so that the fabric was not loose. We noticed some slight fabric tearing around one of the grommets that was attaching the corner of the fabric to the milk crates (*Figure 19*). To address this issue, we altered the row cover design to increase the durability of the row covers by employing a heavier fabric. The heavier fabric is less permeable to light (60% permeability), but will be more resistant to tearing. We also noticed that the 1" carabiners were difficult to attach to some of the milk crates made with thicker walls. To address this, we altered our recommendations and user manual to include slightly larger carabiners. This will ensure that it is easy to attach the covers to milk crates from any manufacturer. Wind speed reduction testing could not be conducted with the row covers because the anemometer was too large to fit inside the covers. However, during wind gusts, we qualitatively compared the wind speeds inside and outside of the row covers by holding one arm inside the covers. There was a noticeable difference between these wind speeds, and even during strong gusts, the wind inside the covers felt only like a light breeze.

Opening the row covers confirmed that the process is simple and control over the fabric is maintained throughout the transition. The process took roughly one minute to complete. Given the size of the test setup, we can estimate that it would take a worker at Higher Ground Farm roughly four minutes to open or close the row covers on one planter row.

Observing the row covers while in the "open" position revealed that the carabiner attachment mechanism kept the row covers from flapping in the wind (*Figure 20*). The placement of the carabiners in the fabric (at the end of the fabric width and at half the width) ensured that the covers did not take up a lot of space behind the row of milk crates while in the open position. The covers were left in this position overnight during rainy weather, and they were inspected for damage or weakness the next day. This showed that the durability of the row covers is not impacted by rain.

Prototype testing of the ivy wall barriers and row covers confirmed that they effectively reduce wind speeds, and are durable in windy conditions. The exercise of constructing the barriers allowed us to provide specific, easy to follow instructions in the user manual.

Figure 18: **Row Cover Testing (Closed)**

Figure 19: **Fabric Damage**

Figure 20: **Row Cover Testing (Open)**

RECOMMENDATIONS

The goal of this project was to design wind barriers that provide effective protection for crops at Higher Ground Farm and other urban rooftop farms. This section contains our recommendations for how to accomplish this, for both John Stoddard and other urban rooftop farmers.

I. RECOMMENDATIONS FOR HIGHER GROUND FARM

Our barriers were designed to address the unique conditions present at Higher Ground Farm. We recommend constructing ivy walls and placing them around the tomato planter rows to mitigate the wind damage to the tomato plants. Ivy walls have the height needed to fully protect tall tomato plants, and the stability to stay upright in fast wind conditions due to their triangular supports, wide base, and the soil-filled milk crates that weight them down. We recommend using three soil-filled milk crates, with a mature Boston ivy plant in the middle milk crate. Mature ivy will function better than growing the ivy from seeds because the infant ivy's growth could be stunted by the windy conditions on the roof.

The barriers should surround the planter rows on all sides to adequately protect the tomato plants, given the wind conditions present on the farm. Stoddard uses a rotating crop system in which the type of plant that is seeded in a section of planter rows changes every year on a set rotation. As such, the number of ivy walls needed each year will vary with the dimensions of the section of planter rows that will contain tomato plants. Based on the dimension of all planter row sections, 10 ivy wall barriers would be the maximum number needed for a season. The cost of constructing 10 ivy wall barriers would be $896.86, at an individual cost of $89.69 per barrier. Four ivy walls were constructed during this project for testing purposes, and a breakdown of the cost for these barriers can be found in Appendix E. Boston ivy plants were not purchased for the prototype testing because we did not have enough time to adequately grow the ivy on the lattice. Instead, a price for the ivy plants was found online. This price, as well as the prices of the materials we purchased for prototype testing, were used to estimate the individual cost of a single ivy wall barrier. The user manual that we created contains detailed instructions about how to construct and assemble the ivy wall barriers.

We recommend that John Stoddard use row covers to protect the remaining planter rows. These rows all contain plants that grow close to the soil, and row covers are a cheap solution that provides complete coverage and take up minimal space. Row cover hoops should be placed one-foot deep into the soil of the planter rows every four to five feet. Row cover fabric should be cut to size so that one foot of fabric can be tucked underneath the milk crates, and the other end can overhang enough so that the carabiner fasteners can be secured to the sides of the milk crates. For the planter rows at Higher Ground Farm, this width should be roughly 6’ 8”. The length is less important, as the fabric can be placed in pieces and overlapped to cover the entire length of a row. Holes for the carabiners, with grommets to protect the fabric, should be placed every four to five feet, in line with the placement of the hoops. Holes for attachment to the milk crates should be placed an inch in from the overhanging end of the fabric, and holes for attachment to the hoops should be placed 2 feet in from the overhanging end. When pulling back the row covers to expose the crops, the fabric should be unfastened from the milk crate one carabiner at a time, and refastened open to the other side of the milk crate. Each carabiner should be refastened open before moving on to unfasten the next carabiner. Using this method will ensure that the most control possible is maintained over the plastic’s movement at all times, and prevent the plastic from flapping in the wind and disrupting farm work. The cost of placing row covers on all the Higher Ground Farm planter rows that don’t contain tomato plants would be $1240.32, at a cost of $25.84 per planter row. This cost was estimated assuming that the hoops and fabric would be bought in bulk, and that bulk split rings would be used instead of carabiners, as they are much cheaper this way. For the prototype testing, these items were not bought in bulk. 4.3' of row covers were constructed during this project for testing purposes, and a breakdown of the cost for these covers can be found in Appendix E. The costs and sources for the bulk materials used in calculating the costs listed above are also included in this appendix. The user manual that we created contains detailed instructions about how to assemble and use the row covers and the attachment mechanism. We are not recommending that John use grass barriers because the walking paths between rows on his farm are too small to adequately fit grass barriers.

II. Recommendations for Other Rooftop Farms

The previous recommendations apply specifically to Higher Ground Farm. However, our barrier designs can be used on other rooftop farms. We recommend that any rooftop farm that struggles with wind damage consider row covers. This design is inexpensive and simple, and it protects crops completely from wind damage. Modifications to the attachment mechanism may be required in other situations, as our design relies on the milk crate planters used at Higher Ground Farm. For example, on rooftop farms that have dirt covering the entire rooftop, weights such as bricks might be used to secure the ends of the fabric instead of carabiners. Covering an 18' x 2' area with row covers would cost roughly $25.84. For any crop that is too tall to be effectively covered by row covers, we recommend our ivy wall design. This design is effective at protecting larger crops. This design can be applied to areas of any size, as the individual wall units attach together easily and can be used to create corners. As such, creating a perimeter of ivy walls around appropriate crops is feasible in any situation, provided the perimeter of the intended protected area is calculated. The ivy wall barriers are each 8' wide by 5' tall, and each individual barrier costs $89.69. Using this information, the number of individual ivy walls needed can be calculated, as well as the total cost.

CONCLUSION

The goal of this project was to design wind barriers that protect crops at Higher Ground Farm and other urban rooftop farms. This goal was accomplished by designing, building, and testing a set of wind barriers, and providing a user manual so that these barriers could be used on other rooftop farms. The designs provided will reduce wind damage to the crops, increasing crop yield and overall profit for Higher Ground Farm and other rooftop farms.

Prior to the completion of this project, there was a gap in information regarding effective wind barriers for rooftop farms. Through our work, we filled this gap by compiling information about rooftop wind dynamics, wind damage to crops, and ground-level wind barriers. We also refined the properties of these barriers to meet the unique needs of rooftop farms, developed and tested these designs, and created a user manual to relay our wind barrier design recommendations. By compiling information, we have created a resource for existing and future rooftop farmers to learn about unique issues of wind damage on urban rooftop farms and to compare existing wind barrier designs.

There is still more research to be considered in the future. One concern that several rooftop farmers and wind barrier experts had was the impact of seed spreading when using organic grass barriers. Rush wheatgrass and little bluestem could potentially spread their seeds into the soil of the crops themselves. Since these barriers were not included in our recommendation to our sponsor, we did not perform testing in response to this concern. As such, anybody planning on using organic grass barriers should take this into consideration.

Another future consideration would be more rigorous wind speed testing over several months. Due to time constraints, we were only able to perform one day of wind speed testing at Higher Ground Farm. This data allowed us to better understand the wind patterns at the farm.

However, with several months of wind data from Higher Ground Farm, we would be able to more accurately characterize wind behavior with statistically-significant data.

Rooftop farms and urban agriculture make cities more sustainable. Direct environmental benefits of rooftop farms include reducing energy consumption, improving storm water management, improving city air quality, and reducing carbon emissions. Cities are also supplied with local produce by utilizing urban rooftops, which reduces travel distance of fresh produce, increases urban food security, and helps to prevent the over-irrigation of rural areas. By designing wind barriers and increasing crop yield at rooftop farms, this project supports the growth of urban agriculture and a more sustainable food system.

References

Ackerman, K., Conard, M., Culligan, P., Plunz, R., Sutto, M.-P., & Whittinghill, L. (2014). Sustainable Food Systems for Future Cities: The Potential of Urban Agriculture. *The Economic and Social Review*, *45*(2, Summer), 189–206.

Boston Ivy. (n.d.). Retrieved March 5, 2017, from http://www.bostonivy.net/

Brandle, J. R., Hintz, D. L., & Sturrock, J. W. (2012). *Windbreak Technology*. Elsevier.

Brandle, J. (2017, February 6). Phone interview.

Center for Green Roof Research. (2017). Retrieved March 6, 2017, from http://plantscience.psu.edu/research/centers/green-roof

City of Defiance Stormwater Program. (2012). Retrieved March 6, 2017, from http://www.cityofdefiance.com/main/index.php/divisions/storm water-ms4

Combined Sewer Overflow Control Program. (2016, September 13). Retrieved March 6, 2017, from http://www.mwra.state.ma.us/03sewer/html/sewcso.htm

The Freshwater Society. (2013). Urban Agriculture as a Green Stormwater Management Strategy. Retrieved February 27, 2017 from http://www.arboretum.umn.edu/UserFiles/File/2012%20Clean%20Water%20Summit/Freshwater%20Urban%20Ag%20White%20Paper%20Final.pdf

Good, J., & Good, A. (2012, December 12). Taming the floating row cover | Rodale Institute. Retrieved October 3, 2016, from http://rodaleinstitute.org/taming-the-floating-row-cover/

Green Roof Benefits. (n.d.). Retrieved March 6, 2017, from https://www.nps.gov/tps/sustainability/new-technology/green-roofs/benefits.htm

Heisler, G. M., & Dewalle, D. R. (1988). 2. Effects of windbreak structure on wind flow. *Agriculture, Ecosystems & Environment*, *22*, 41–69. http://doi.org/10.1016/0167-8809(88)90007-2

Henkel, T. (2017, February 23). Phone interview.

Kunicki, E., Cebula, S., Libik, A., & Siwek, P. (1996). THE INFLUENCE OF ROW COVER ON THE DEVELOPMENT AND YIELD OF BROCCOLI IN SPRING PRODUCTION. *Acta Horticulturae*, (407), 377–384. https://doi.org/10.17660/ActaHortic.1996.407.48

Learn how much it costs to Build a Greenhouse. (n.d.). Retrieved February 20, 2017, from http://www.homeadvisor.com/cost/outdoor-living/build-a-greenhouse/

Levenston, M. (2010). Brooklyn Grange will be a 1 acre rooftop farm. Retrieved March 05, 2017, from http://www.cityfarmer.info/2010/04/29/brooklyn-grange-will-be-a-1-acre-rooftop-farm/

Little Bluestem Plant Fact Sheet. (2002). United States Department of Agriculture Natural Resources Conservation Service. Retrieved from https://plants.usda.gov/factsheet/pdf/fs_scsc.pdf

Mandel, L. (2013). *EAT UP: The Inside Scoop on Rooftop Agriculture*. New Society Publishers.

McAneney, K. J., Judd, M. J., & Trought, M. C. T. (1984). Wind damage to kiwifruit (Actinidia chinensis Planch.) in relation to windbreak performance. *New Zealand Journal of Agricultural Research*, *27*(2), 255–263. http://doi.org/10.1080/00288233.1984.10430427

Novak, A. (2016). The rooftop growing guide: how to transform your roof into a vegetable garden or farm. Berkeley: Ten Speed Press.

Proksch, G. (2014). Urban Rooftops as Productive Resources: Rooftop Farming versus Conventional Green Roofs. *ARCC Conference Repository*, *0*(0). Retrieved from http://www.arcc-journal.org/index.php/repository/article/view/358

QUALITY CONTROLLED LOCAL CLIMATOLOGICAL DATA (final) HOURLY OBSERVATIONS TABLE. (2017, January 22). National Oceanic and Atmospheric Administration. Retrieved from https://www.ncdc.noaa.gov/qclcd/QCLCD?prior=N

Rhodus, T. (n.d.). Parthenocissus tricuspidata. Retrieved March 5, 2017, from http://hvp.osu.edu/pocketgardener/source/description/pa_idata.html

Rifkin, G. (2011, May 18). Cash Crops Under Glass and Up on the Roof. Retrieved February 20, 2017, from http://www.nytimes.com/2011/05/19/business/smallbusiness/19sbiz.html

Roehr, D., & Kunigk, I. (2009). Metro Vancouver: Designing for Urban Food Production. *Berkeley Planning Journal*, *22*(1). Retrieved from http://escholarship.org/uc/item/3dr3d679

"Rush" Intermediate wheatgrass. (2013). United States Department of Agriculture Natural Resources Conservation Service. Retrieved from https://www.nrcs.usda.gov/Internet/FSE_PLANTMATERIALS/publications/idpmcrb12036.pdf

Sanyé-Mengual, E., Orsini, F., Oliver-Solà, J., Rieradevall, J., Montero, J. I., & Gianquinto, G. (2015). Techniques and crops for efficient rooftop gardens in Bologna, Italy. *Agronomy for Sustainable Development*, *35*(4), 0. http://doi.org/10.1007/s13593-015-0331-0

Sivak, J., Dobbins, R., Christiner, M., & Ndegwa, A. (2010). *Rooftop Wind Turbine Feasibility in Boston, Massachusetts* (pp. 1-92, Rep.). Worcester, MA: WPI.

Sutton, R. (2017, February 6). Phone interview.

Thomaier, S., Specht, K., Henckel, D., Dierich, A., Siebert, R., Freisinger, U. B., & Sawicka, M. (2015). Farming in and on urban buildings: Present practice and specific novelties of Zero-Acreage Farming (ZFarming). *Renewable Agriculture and Food Systems*, *30*(1), 43–54. http://doi.org/10.1017/S1742170514000143

Throness, A. (2017, January 20). Phone interview.

Urban heat island. (2012, April). Retrieved February 05, 2017, from http://glossary.ametsoc.org/wiki/Urban_heat_island

Weather History for Worcester, MA | Weather Underground. (n.d.). Retrieved May 1, 2017, from https://www.wunderground.com/history/airport/KORH/2017/4/24/DailyHistory.html?MR=1

Appendix A: Interview with Urban Agriculture Entrepreneur

I. Introduction Script

Moderator introduces himself and thanks participant for giving up their time to be interviewed. Moderator informs interviewee that this interview should only take about 30 minutes of their time. "This interview is part of a project to design wind barriers for Higher Ground Farm, a rooftop farm located here in Boston. We are currently considering three barrier designs: wheatgrass barriers, row covers, and ivy walls. I will be asking you some questions about your experiences with wind and wind damage at your farm. I will then ask you about solutions to the wind problem. Any input you can give related to designs that you have tried or that you have seen implemented, as well as the design's effectiveness, will be greatly appreciated. In addition, you have the option to retain your anonymity. If you choose to remain anonymous, no personal identifying information such as your name, or the name of your farm, will be included in our final report. If you do not choose to remain anonymous, you will be given the opportunity to review any quoted material from this interview before it is published in our final report."

II. Guiding Questions

- How does wind impact your farm?
    - How often do wind-related problems occur?
    - What crops are most/least affected by wind damage?
    - How does the wind specifically damage crops?
    - How costly overall is the damage? (financially, supplies, time, crop yield)
- Have you implemented wind shielding or any other way of addressing wind damage?
    - If so:
        - Overview of the design?

        - What was the development process like? Were you directly involved in the development?
        - What materials were used? Why?
        - What was the overall cost?
        - How effective is the design?
    - If not:
        - Why not?
        - Do you have any way of dealing with wind? Is wind at all an issue to you?
        - Are you considering implementing some form of wind shielding?
        - Have you seen other urban farms implement some form of wind shielding?
    - Would you consider implementing any of our current designs on your farm if they were shown to be effective?
- Are there any other weather or natural conditions that pose a significant threat to crop health and yield?
    - Do you have methods to address them?
        - If so, what are they?

Thank the interviewee for their time.

Appendix B: Focus Group of Higher Ground Farm Volunteers

I. Introduction

Moderator introduces himself and thanks participants for giving up their time to be in the focus group. "This focus group is part of a project to design wind barriers for Higher Ground Farm in Boston. At this point, we have developed several designs intended to protect crops from wind damage. Through this focus group, our goal is to determine how each design could potentially disrupt farm work."

II. Rules and Guidelines

"We want to create an atmosphere where all participants feel comfortable sharing their honest opinions. To accomplish this, I ask that all of you remain courteous and respectful if you have an opinion that differs from another participant. Please do not talk over or interrupt other participants when they are sharing their thoughts, and make sure that everyone has a chance to voice their opinion. Please also keep in mind that all responses will be anonymous, and no identifying information such as your names, gender, or ages will be included in our final report."

III. Questions

1. Have you noticed wind damage affecting the crops at Higher Ground Farm?
    a. *Show participants images with examples of wind damage.*

"We have developed a set of potential designs and have concept images for each design. *Briefly explain designs and send reference images.* Based on your experiences working at the farm, think about how these designs would impact farm work."

2. Which design do you think would inhibit farm work the most?
    a. Why? What features of the design do you think would cause the most interference?

    b. Would you change anything about this design to make it less disruptive to work around?
3. Which design do you think would inhibit farm work the least?
    a. Why? What features of the design do you think make it least disruptive?
    b. What would you change about the design to make it even less disruptive?
4. How would the other designs interfere with routine tasks?
    a. What would you change about them to make them less disruptive?
5. How difficult do you think it would be for you as a HGF volunteer to assemble any of these barriers for John if you were provided with the raw materials, and there was already a constructed barrier on the farm for reference?
    a. Do you think any one of the designs would be more difficult than the rest? Why?
    b. Do you think any of the designs would be easier than the rest? Why?
6. Are there any of the designs that you think would not be durable enough to withstand the conditions you've experienced on the roof?
    a. What experiences have you had that make you think the design(s) would not hold up?
7. Any other thoughts?

Thank the participants for their time.

APPENDIX C: INTERVIEW WITH WIND BARRIER EXPERT

I. INTRODUCTION SCRIPT

Moderator introduces himself and thanks participant for giving up their time to be interviewed. Moderator informs interviewee that this interview should only take about 30 minutes of their time. "This interview is part of a project to design wind barriers for Higher Ground Farm, a rooftop farm located in Boston. I will be asking you some questions about your experience with wind barriers. I will also be asking for your thoughts on our current designs. Any thoughts or critiques you can offer for our designs will be greatly appreciated. For your knowledge, you have the option to retain your anonymity. If you choose to remain anonymous, no personal identifying information such as your name, or the name of your organization, will be included in our final report. If you do not choose to remain anonymous, you will be given the opportunity to review any quoted material from this interview before it is published in our final report.

Our current designs are row covers, wheatgrass barriers, and ivy walls. I'll briefly explain each one to give you context for the discussion. Row covers are sheets of perforated polypropylene that are secured above crops. Their shape is held with metal hoops placed at intervals along the crop rows. Wheatgrass barriers will consist of a milk crate filled with soil and seeded with Rush wheatgrass. Ivy walls will consist of a wooden trellis in a wooden frame. 3 milk crates, filled with soil with one Boston ivy plant in the middle crate, will be placed in a holding tray at the bottom of the trellis and the ivy will be allowed to grow and attach itself to the trellis."

II. QUESTIONS

1. Are there any barrier designs that you've seen successfully implemented for the purpose of protecting crops that would be viable for a rooftop farm?
    a. How successful were these designs at reducing wind speed?
2. We understand that trees and shrubs are usually the best option for a wind barrier due to the large surface area provided by the leaves, and their ability to break up wind without causing turbulence. Obviously, trees are not a viable solution on a rooftop. What wind barrier designs are you familiar with that emulate these qualities?
    a. Have you encountered any lightweight and affordable ways to implement these design(s)?
    b. How effective were these design(s) at reducing wind speed?
    c. Are there any other barrier designs that you have encountered that you think would be viable in our situation? If so, how effective were they?
3. Which of our designs do you think will be the most effective at reducing wind speeds in the protected region?
    a. Why?
    b. Can you think of any improvements we could make that would make this design even more effective?
4. Which of our designs do you think will be the least effective at reducing wind speeds?
    a. Why?
    b. Can you think of any improvements you would make to this design to increase its effectiveness?

5. We recently took wind speed and direction measurements on the rooftop farm. While the results of these measurements are not statistically significant, they have given us a basic understanding of the minimum wind strength that our barriers must be able to operate in. The strongest wind we measured that day was 9.9 mph. Based on your experience, do you think any of our designs will not be durable enough to withstand long-term exposure to wind on the roof?
    a. If so, what would you change about those designs to make them more durable?

Thank the interviewee for their time.

APPENDIX D: INTERVIEW WITH RUSS LANG GUIDE SHEET

I. INTRODUCTION

Moderator introduces himself and thanks participant for giving up their time to be interviewed. Moderator informs interviewee that this interview should only take about 30 minutes of their time. "We are conducting this informal interview to get your input on the structural integrity of our barrier designs, as well as any advice you can give us in the building and testing stages of our project. If you choose to remain anonymous, no personal identifying information such as your name will be included in our final report."

II. GUIDING QUESTIONS

- Do you think our designs will remain standing over long periods of time in high winds on a Boston rooftop?
    - Possible sub-topics:
        - Which barriers do you think are better and for what reasons?
        - Are there certain features of each design that are beneficial?
        - Are our choices of hardware appropriate?
        - What edits can we make to our designs to make them more structurally sound?
        - Are our choices of building materials appropriate?
        - Do you think we should use a paint-primer, or use pressure treated lumber?
- In the testing stage, we were considering using fake ivy to simulate real ivy, will fake ivy simulate the aerodynamic properties of real ivy?
    - Possible sub topics

        - Are there any other ways of testing the designs effectiveness?
- Do you have any other questions or input on our project?

Thank the interviewee for their time.

APPENDIX E: PROTOTYPE WIND BARRIER COSTS

Item	Quantity	Source of Item	Total Cost
Wooden lattice	4	Home Depot	$52.82
⅜" Washer	32	" "	$4.80
⅜"x4.5" Carriage Bolt	24	" "	$20.92
⅜" Wing Nut	32	" "	$20.80
⅜"x6" Carriage Bolt	8	" "	$8.56
⅝" Screw	1 Jar	" "	$8.99
4"x8"x0.5" Plywood Sheet	2	" "	$51.10
2"x4"x8' Pine Plank	24	" "	$71.76
Boston Ivy Plant (mature)	4	NatureHills.com	$119.00

Table 5: **Cost of Four Ivy Wall Barriers**

Item	Quantity	Source of Item	Total Cost
Row Cover Fabric ("Garden Quilt Cover")	6' x 20'	Gardener's Supply Company	$12.95
Row Cover Fabric ("Garden Quilt Cover")	6' x 50'	" "	$23.95
Row Cover Hoops ("Super Hoops")	6	" "	$22.95
"Standard" Row Cover Hoops	100	Arbico Organics	$106.00
½" Grommets	12	Home Depot	$3.44
1" Carabiners	10	" "	$8.95
1" Metal Split Rings	100	Amazon.com	$5.60

Table 6: **Cost of Row Covers for 4.3' of Planter Row**

APPENDIX F: WIND MEASUREMENT RAW DATA

Time	Location 1		Location 2		Location 3		Location 4		Location 5		Location 6	
0:30	4.5	N	3.9	SE	7.1	W	3.5	N	5.3	N	4	SW
1:00	4.8	E	6	NW	5.3	NW	3.5	E	4.7	N	4.8	N
1:30	5.9	E	4.3	SE	3.7	NW	5.4	E	5.5	N	5.7	S
2:00	5.7	NE	6	SW	4.9	SW	7.5	N	4.8	NW	5.7	SW
2:30	7	N	7.6	NW	3.4	S	3.9	NW	5.5	N	3.5	SW
3:00	6.1	NE	2.4	E	5.2	N	7.1	S	7.1	E	5.4	S
3:30	5.9	S	2.5	SE	5.2	N	6.1	N	5.7	W	3.2	N
4:00	6.2	SE	7.6	NW	4.3	SW	2.9	E	6.6	NE	2.5	NW
4:30	6.2	W	7	SE	5.8	S	4.4	N	6.6	N	4.4	NW
5:00	5	E	4.7	SE	3.9	W	8.8	N	6.2	NW	4.7	E
5:30	5.7	E	2.9	E	5.3	SW	8.8	NW	4.8	W	3.7	W
6:00	9.4	N	5.5	N	5.5	S	6.2	E	4.7	N	2.8	W
6:30	5.3	E	4.2	E	5.2	S	6.7	N	6.1	N	5.3	N
7:00	6.5	E	4.2	N	7.3	SW	4.8	N	5.7	NE	5	E
7:30	6.3	W	1.8	SE	4.1	NW	7.1	N	4.3	N	2.8	NW
8:00	6.1	S	5.9	NW	5.4	SW	7.5	E	6.3	S	4.3	NW
8:30	5.8	N	3.9	N	7	NW	4.2	S	4.4	NE	5.8	SW
9:00	6.6	E	3.8	E	3.4	SE	4.8	N	5.4	N	5.4	NW
9:30	7.9	W	5.2	W	4.5	S	5.9	NE	4.7	NE	5.2	W
10:00	6	E	5	S	4.9	SW	6.1	E	5.3	E	6.5	NW
10:30	8.6	S	8.1	N	4.9	W	5.8	NE	6.2	NE	6.1	W
11:00	6	N	4.1	S	5.7	S	5.7	N	4.7	E	6.2	SE
11:30	6.1	NE	4.8	W	5.8	W	3.7	E	5	N	5.9	SE
12:00	6.8	N	3.2	E	4.1	SW	4.7	E	4.1	N	4.3	NW
12:30	6.8	NW	5.7	SE	4.3	W	7.3	NE	4.3	NE	4.3	W
13:00	6.6	E	5.8	S	3.2	W	5.5	NE	2.5	N	5.5	NE
13:30	6.7	S	6.1	S	3.2	NW	4.7	NE	5.3	E	3.3	NW
14:00	6.7	E	4.8	S	4.5	N	6.2	E	4.8	N	4.8	NW
14:30	9.9	NE	5.2	E	4.5	W	5.7	W	4.8	N	4.5	N
15:00	8.8	E	4.8	NW	4.5	W	5	N	4	N	5.3	SW

***Table 7:* On Site Wind Measurement Data**

	MONDAY		TUESDAY		WEDNESDAY		SATURDAY	
TIME (mins)	Out	In	Out	In	Out	In	Out	In
0:00	6.6	1.9	4.5	2.4	1.4	0.7	11.2	4.4
0:30	6.6	2.3	8.3	4.1	1.6	1.1	8.7	3.4
1:00	4.7	2.3	10.4	3.5	2.2	1.3	7.2	5.3
1:30	5.3	2.3	10.3	5.5	1.9	1.2	7.2	3.2
2:00	4.9	1.2	5.8	3.5	4.2	1.8	7.1	3.3
2:30	6.1	1.1	9.6	6.2	9.6	1.8	10.3	2.3
3:00	5.7	1.7	8.1	3.9	11.6	1.9	6.8	5.2
3:30	4.7	2.7	8.8	4.5	4.2	2.4	10.3	5.5
4:00	3.8	3.5	5.5	2.7	6.6	2.8	8.6	7
4:30	3.5	4.3	4.0	3.7	2.2	1.2	11.7	3.8
5:00	2.7	4.4	4.8	2.3	3.7	2.1	8.6	3.8
5:30	3.0	1.7	7.8	4.4	4.1	0.9	8.2	5.5
6:00	3.9	2.5	11.4	4.8	7.9	0.6	11.2	3.7
6:30	3.2	2.8	11.3	5.3	7.9	1.6	6.3	2.5
7:00	3.3	2.8	5.9	2.9	6	1.3	4.4	2.7
7:30	6.8	2.4	5.2	2.3	6.3	0.7	7.9	1.4
8:00	6.8	3.5	4.9	2.3	6.3	0.6	8.5	2.2
8:30	3.7	3.0	7.6	2.3	6.5	0.2	8.5	1.9
9:00	5.9	3.0	7.8	3.7	5	1.8	4.3	1.9
9:30	5.7	3.3	7.1	3.9	5.5	1.3	5.2	2.9
10:00	5.4	4.4	4.3	2.1	1.9	0.9	5.9	3.4
10:30	5.5	4.4	3.9	3.5	7.1	0.4	5.9	5.5
11:00	5.9	2.9	6.1	4.7	7.2	2.5	11.0	3.5
11:30	7.0	2.9	7.0	3.9	8.6	2.5	7.8	4.5
12:00	5.8	3.8	5.7	3.4	8.8	1.8	11.1	8.1
12:30	5.8	5.5	2.2	2.4	7.6	1.2	12.5	8
13:00	7.6	5.0	4.4	4.1	5.7	1.2	13.0	4.3
13:30	8.2	4.1	4.0	1.7	5.7	1.6	13.2	4.9
14:00	6.0	4.1	4.3	2.1	7.5	0.7	12.1	4.9
14:30	5.3	2.7	3.5	4.0	10.7	1.1	13.3	4.2
15:00	7.0	1.3	7.5	2.5	5.3	1.2	12.1	4.2

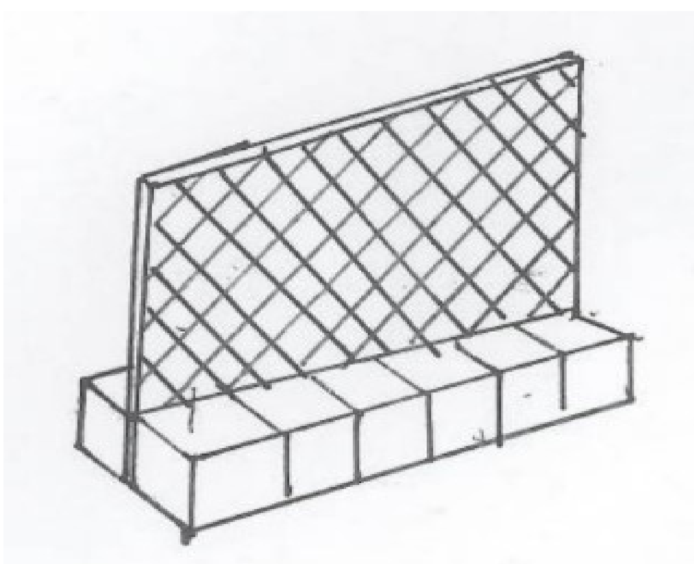
Table 8: **Ivy Wall Wind Speed Measurements**

APPENDIX G: REJECTED WIND BARRIER DESIGNS

This appendix describes designs from earlier stages of the project. These designs were eventually modified or rejected due to flaws or deficiencies. This section will discuss each design and our thought process when designing it, and the reason(s) that we decided to not include that design in our recommendation.

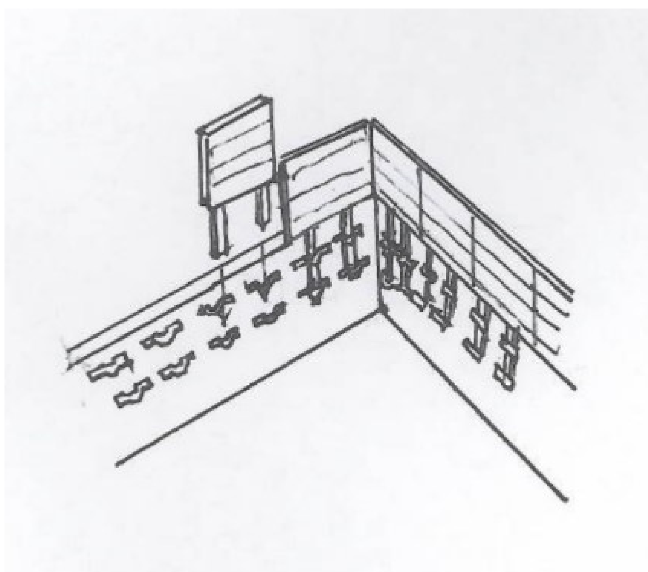
I. INEXPENSIVE IVY WALL

The inexpensive ivy wall design was the initial iteration of our ivy wall design. This design was intended to be inexpensive, and to rely on the weight of soil in milk crates to support the lattice. A sketch of this design is shown below. However, Russ Lang questioned the stability of this design in our interview. He suggested that we add gussets, as the lattices are flimsy and would need support during harsher weather conditions. We then modified this design, and these modifications resulted in the final ivy wall design that was tested and ultimately recommended to John Stoddard.



II. Bracket Mounted Barriers

The bracket mounted barrier was one of our initial designs that we developed during ID2050. This design was created before we had visited Higher Ground Farm, so we had limited knowledge of the farm's layout. This design was developed because it is maneuverable, lightweight, durable, and easy to assembly. It also did not require any space on the ground, so it would be usable regardless of the space available at Higher Ground Farm. We knew that there were concrete parapet walls surrounding the perimeter of the roof. As such, we developed a basic wall-type wind barrier that would attach to the parapet walls with brackets. As shown below, the walls would be attached to stakes, which would slide easily into the brackets on the parapet wall. However, we learned that solid wall-type wind barriers create turbulence that can cause more wind damage to crops. As such, we did not include this design in our recommendation.



III. Row Sized Greenhouses

The row sized greenhouse design was developed after some initial research into conventional wind barriers. We learned that greenhouses are one of the most effective wind barrier, as they completely protect all enclosed crops from wind damage. However, building a large greenhouse at Higher Ground Farm was not feasible, as it would be well over John Stoddard's budget. As such, we developed our own row sized greenhouse design. The goal of this design was to be affordable while fully protecting crops. As shown below, this design simulates the conditions inside a greenhouse by completely surrounding the crops. However, this design was still much more expensive than row covers. In addition, this design would require much more construction time. As such, we did not include this design in our recommendation.