A Floating Farm for Hydroponic Crop Cultivation in Small Island Developing States

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On my honor as a University Student, I have neither given nor received unauthorized aid on this assignment as defined by the Honor Guidelines for Thesis-Related Assignments

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***Abstract*— This capstone project aims to modify and finalize an existing hydroponic crop cultivation (HCC) system, called the "Fold-out-Farm," to operate on a floating platform in Small Island Developing States (SIDS) that are susceptible to food insecurity due to natural and economic factors. Specifically, when SIDS are hit by natural disasters, crops and agricultural infrastructure can be severely damaged, causing many people to suffer from a lack of both food access and job opportunity. The Fold-out-Farm is completely self sufficient – it has its own water collection system, solar based power generation, and on-board growing pods. The unit can float to combat disaster consequences from incidents such as hurricanes. Specifically, the project is working to add a rainwater harvesting system and validate the structural integrity of the unit during a flood. The farm is designed to use off-the-shelf nutrient solutions to grow a variety of crops and the team will find the most suitable option. The team will also expand the market niche for the HCC system by determining the optimal use for the product in urban food deserts, refugee camps, and rooftop gardens. The approach taken has involved communication and research to understand the needs of those who could benefit from a Fold-out-Farm, as well as various testing methods for crops and structure of the unit. Testing has been done through expert surveys, estimation of structural performance, simulation software analysis, and evaluation of crop yield from the unit relative to a control crop grown in soil. Results will be continuously measured, first in testing the system's ability to deliver water, sun and nutrients to growing modules, its crop yield, and stability in an open water test in the Rivanna river, and finally when presenting the design to sponsors and potential users. Future researchers may build upon these findings to further improve the unit and its potential use to ensure that it is understandable and acceptable to the communities who will be using it. The project will have a market-ready product capable of reducing food insecurity in SIDS and potentially in urban food deserts, refugee camps and rooftop gardens in land scarce areas.**

I. MOTIVATION

The current food systems are under pressure from various factors such as population growth, the demand for animal products, the availability of fertile soil, and shifts in climate regimes. As we move into the next century, climate change is expected to have a negative impact on the four pillars of food security - availability, access, utilization, and stability. Human-induced climate change caused by carbon dioxide emissions exacerbates the current stresses on these pillars through increasing temperatures, changing precipitation patterns, and more frequent, intense extreme weather events like floods, droughts, and hurricanes [8]. Small Island Developing States (SIDS) located in the Caribbean, Pacific, Indian Ocean, and South China Sea, despite being far from homogeneous, are particularly vulnerable to the impacts of climate change on food security due to their small land area, remote geography, and susceptibility to extreme climate events [7].

This project aimed to create sustainable food sources in Caribbean SIDS, which frequently face high-risk natural disasters like hurricanes and floods, as a humanitarian service. The project developed a template for a crop cultivation system that can be mostly self-sufficient, withstand extreme weather and associated hazards, and provide a supplementary power supply when necessary. To determine the most suitable system to meet this need, several alternatives were analyzed. The analysis concluded that a solar-powered floating Dutch bucket hydroponics system was the best fit for the selected criteria. This system's selection, design, and a prototype test will be discussed. Specifically, this project will be a crop cultivation system that is a mostly self-sufficient sustainable food source, withstands extreme weather and associated hazards, and provides supplementary power supply when necessary.

II. BACKGROUND

A. Food Security

Worldwide, some of the most at-risk regions for food insecurity are coastal communities and Small Island Developing States (SIDS) (includes nations in the Caribbean, Pacific, and Indian Oceans) due to a variety of natural and economic factors. Making up approximately 1% of the global population [1], SIDS face unique challenges due to their small land area, remote geography, and susceptibility to extreme climate events. Current food systems in place face mounting pressures from population growth, availability of fertile soil as well as an increasing rate of extreme weather. According to the UN, climate change is projected to negatively impact the four pillars of food security – availability, access, utilization, and stability – during the 21st century [2]. The economy of Caribbean nations is heavily reliant on agriculture, with significant contributions to their Gross Domestic Products ranging from 7% to 17%. However, despite their capacity for agricultural production, most countries in the region are highly dependent on imported food. In fact, the proportion of food consumed in the region that is imported has risen from 40% to 60% since 1990, with over half of the countries importing more than 80% of their food. This increased reliance on imports, combined with the growing frequency of natural disasters caused by climate change, creates market volatility and food insecurity in the region.

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B. Climate Change

Climate change is exacerbating the current stresses on these pillars through increasing temperatures, changing precipitation patterns, and the increase in frequency, duration, and intensity of extreme weather events like floods, droughts, and hurricanes. According to the University of the Bahamas [3], global mean sea-level is currently rising at a rate around 3.6 mm per year. This rate only increases with higher emission scenarios with possible meters of sea level rise by 2300. This is detrimental for the future of coastal communities that support tourism, fisheries, and agriculture industries in the region. SIDS are also vulnerable to extreme weather events which have been exacerbated by the changing climate. These weather events can result in damage at a nationally significant scale since Caribbean SIDS have small economies, areas, and populations. In 2017, Hurricane Maria caused damages that amounted to more than 225% more than the annual GDP of Dominica [4]. While the effects of climate change will affect every nation, region, and economy of the world, Caribbean SIDS are especially vulnerable due to their close connection to coastal environments.

C. Current State of Agriculture

The Caribbean region has a long history of small-scale farming and food production, with many rural households having a deep connection to the land and a tradition of cultivating their own crops. These farmers often utilize traditional techniques that have been passed down through generations [12], such as intercropping, which involves planting multiple crops together in close proximity to maximize yield and use resources more efficiently. This method has numerous benefits, such as reducing soil erosion, filtering pollutants from the soil, and slowing down runoff [13], which helps to maintain the health of local ecosystems. While some small-scale farmers in the Caribbean have adopted more modern methods of farming, such as greenhouse technology and organic farming, many still rely on agri-chemicals like fertilizers and pesticides to increase the productivity of their crops. However, the use of these chemicals can have negative impacts on the environment, including soil and water pollution and harm to beneficial insects and wildlife. Agriculture is a vital sector of the Caribbean economy, with many countries in the region having large agricultural industries that contribute significantly to their GDP. However, despite this, most nations in the region are heavily reliant on food imports, with many importing over 80% of their food. This trend has been increasing since 1990, leading to greater market volatility and food insecurity in the region [12]. This dependence on imported food also leaves the Caribbean vulnerable to supply chain disruptions and price spikes, which can have devastating impacts on the region's food security.

Despite the challenges faced by small-scale farmers in the Caribbean, there are opportunities for the development of sustainable and resilient food systems in the region. This could include the establishment of cooperative networks and other forms of support for small-scale farmers, as well as increased investment in agricultural research and development to promote more sustainable and efficient farming practices. By prioritizing the development of local food systems and reducing dependence on imports, the Caribbean region can build a more secure and resilient food system that benefits both farmers and consumers alike.

III. EXPLORING ALTERNATIVE MARKET NICHES

Hydroponic Crop Cultivation (HCC) has the potential to address issues associated with food insecurity, sustainability, and socio-economic development. These needs may be better met by identifying the most suitable areas to market HCC. Alternative areas for use of HCC include SIDS and coastal communities, refugee camps, urban food deserts, and rooftop gardens. A survey was conducted to gain insight on how to rank the alternatives by suitability for HCC. Researchers reached out to experts in the field to participate in these surveys for more experienced perspectives. A multicriteria decision analysis was used to discover and quantify expert considerations about various factors in order to compare alternative courses of action. For the purpose of the survey, a definition of the alternatives was provided. SIDS & coastal communities are countries facing specific and increasing challenges due to their geographic characteristics. Refugee camps are temporary settlements built to receive refugees and people in refugee-like situations, including long-term refugee camps. Urban food deserts are areas where people have limited access to a variety of healthy and affordable food. Rooftop gardens are plants grown in containers on the flat roof of a building. The survey asked questions on different criteria including land/space availability, energy use, and human components. For each question, the survey volunteer was to rate the suitability of HCC at each alternative. The rating system was on a scale of 1-5 with 1 being Unsuitable (does not meet the requirements for hydroponic crop cultivation or has significant drawbacks) and 5 being Excellent (the most suitable choice for hydroponic crop cultivation and has numerous advantages). Each criterion was weighted equally. The final ranking of each alternative will be determined by totaling the scores assigned by the survey volunteer for each question. Although each survey volunteer may have a different top-ranked alternative, the survey results will allow for a comprehensive evaluation of the suitability of each alternative based on different criteria, providing valuable insight on the most promising use case for HCC. The survey is ongoing.

IV. RELATED RESEARCH

The foundation of this project was primarily built on previous studies and trials conducted in the area. In this segment, we will showcase two examples of floating agriculture systems that acted as a source of motivation for the ultimate configuration of the system, along with a brief overview of the Dutch bucket hydroponic technique.

For more than three centuries, farmers in Bangladesh have been constructing floating farms utilizing natural materials obtained from the region. The process involves using aquatic weeds like water hyacinth to produce a raft-like platform and planting seedlings in the organic soil. With climate change posing a significant threat, floating farms have become a crucial aspect of providing farmers with sufficient food supply and income [11]. Another example of the floating farm technique can be found in Rotterdam, Netherlands, where a floating dairy farm was opened in May 2019. The goal of this farm is to address concerns about the rising sea levels impacting farmland by raising cattle on the harbor. The structure can resist the harbor's 8-foot tides without tilting more than 11 inches, even under wind speeds of 70 mph [12].

The Dutch bucket method is a hydroponic approach that utilizes individual pots or buckets for cultivating plants. This technique involves filling the buckets with a growing medium like perlite or coconut husks, with a layer of clay pellets underneath for drainage. The pots are arranged along a pipeline or a comparable water supply system that distributes a nutrient solution from a central tank to each bucket. The water can either be drained or recirculated into the system.

V. SYSTEM DESIGN

This system was designed to have microgrid power capability, water collection and storage, as well as resistance to winds and flooding, as specified by the client and previous work. As seen below, the system has an 8 by 8 foot square base, along with four trapezoidal doors that can fold to 45 degrees, maximizing vertical space while minimizing wind and water stress during natural disaster events (Fig. 1, 2). Inside of the system are 2, 100-watt photovoltaic (PV) modules (Fig. 2, 3) as well as a four plant Dutch bucket system, and a water collection rig. Closed-cell foam material under the system provides buoyancy, designed for a 35% submergence. To ensure buoyancy remains while water is collected, the large water-collecting trashcan sits in a hole to be engulfed if full of water.

The electrical system is used to power the pumps in the water collection system. Also, the battery has enough extra power to charge home appliances such as refrigerators and lighting if necessary. Energy storage comes from storage in a 100 amp-hour battery, and an inverter provides 110-volt AC power for use with auxiliary needs.

A. Design Criteria

Mechanical:

The mechanical stress criteria are wind speeds encountered in a Category 1-3 hurricane (maximum of 129 mph) and associated storm surge. Additionally, the structure must provide a horizontal, sheltered platform to support the hydroponics system, and be positively buoyant. The constructability and affordability of the final design are also key considerations. We elected to avoid exotic materials and construction methods, and stipulate that people with common hand tools and readily-available building material should be able to assemble the design using basic construction skills and techniques.

Figure 1. Floating platform, fully folded.

Figure 2. Floating platform, partially folded.

Figure 3. Floating platform, unfolded.

Electrical:

The electrical design criteria are to provide power for 72 hours with no solar gain. The maximum demand was estimated as 1264 watt-hours/day for two pumps, one portable refrigerator, four cell phone chargers and five LED lights. Per the National Renewable Energy Laboratory, peak sun hours at 25° latitude (approximately that of the Bahamas) is 5.5. Assuming system efficiency of 60%, 400W of instantaneous solar input is required (four 100-watt modules) for growing season energy security. A battery of 300 amp-hour capacity could provide up to three days of emergency power. A smaller 100 Ah battery was selected however, to reduce cost and overall system weight in the demonstration prototype [22].

B. Costs

Created during the 2023-24 academic year, the Floating HCC Platform and electrical equipment come out to \$1617.00, and the Dutch bucket system costs a total of \$420.37. The biggest current cost was the water collection system. The goal for this system was to make it functional, replicable and cheap. With the water pumps costing an estimated \$98.00, the total cost of the water system was \$189.81. The large majority of this cost was from the water pumps, which can come much cheaper. Also, if used in mass production, the cost per item would go down severely.

C. Stability and Structural Integrity

The buoyancy of the platform was determined using hydrostatics. Autodesk Inventor was used to verify the weight and center of gravity of the assembled platform. The metacentric height was found to be positive (32.8 ft) indicating a stable platform. Although the center of buoyancy is above the center of gravity by 7.6 inches, due to the platform dimensions the center of buoyancy shifts during heeling and creates an effective righting couple.

Using Autodesk Robot Structural Analysis, we found it most effective to use ¾” plywood as the base and ½” plywood for the walls. Using this ½” plywood reduces the dead weight and is still very effective for offsetting the damage caused by wind loading. ½” plywood can withstand a 35 lb/ft2 force. Therefore, our simulated model can withstand wind speeds of up to 140 mph. The maximum pressure experienced by the platform in a category 3 hurricane is 33.85 lb/ft2, a pressure that is only experienced in concentrated areas of the platform (lower center of one of the sides, or a bottom corner). Thus, it could survive all category 3, and some category 4 hurricanes without material failure.

In the event of a more extreme event, pressure could be experienced along a larger surface if the platform were to lift such that the bottom was exposed. A majority of the wind load would be offset by the angle of the lift and in this case the platform would need to weigh a minimum of 135.4 lbs at the perimeter creating a moment arm to counteract the wind loading force, which the platform easily exceeds. Therefore, based on our simulation, the platform is well equipped to handle a Category 3 hurricane event without tipping. Further simulations were conducted using Autodesk Computational Fluid Dynamics, analyzing the compound forces exerted on the platform by both wind and waves. The results showed resilience when exposed to Category 3 storm conditions, however limitations in our simulation software did not permit estimation of the full range of effects from wave action pitch, roll, and yaw on stability of the platform, or how these wave effects and other turbulence would reinforce wind forces on the structure. Our values are preliminary and may be updated upon further investigation. We recommend that the system be anchored to prevent loss or damage.

D. Water Collection System

The Water Collection System (Fig. 4) uses water catching, holding, and pumping to allow for plant watering when no one can tend to the system, because of a natural disaster or otherwise. This system uses three buckets: A, B and C as listed in Fig. 4. During a natural disaster, the system should be closed. In this case, bucket A, the top bucket, will still be exposed to the outside world and can catch any rain water. This bucket is connected to the system using screws, washers, and Flex Seal. On the side of this bucket, a hole with an elbow adapter and tube takes any collected water to be stored in the large trash can, labeled B. To take water from storage to the plants, a pump takes any water from trash can B to bucket C where it is dispersed to each plant using a series of tubes and adaptors. For water circulation, there is also a vacuum pump going from bucket B to trashcan C, meaning there are two pumps between these containers that take water back and forth. When the pump takes water from bucket C to B, water is pulled from the plants and circulated through the system.

Figure 4. Dutch bucket system.

These timers are set for every 2 hours, offset from each other by 15 minutes. To test this water collection system, sprouted plants were chosen based on their nutrient needs: lettuce and carrots. These crops started their growth in the University of Virginia greenhouse, because of timing needs, and have recently been moved to the hydroponic system. In this system, they were placed in the Dutch buckets and the water circulation system was tested and used. Although the plants have not been in the system for long, they appear healthy and happy thus far.

VI. Conclusions and Future Work

The conclusion of the finalized prototype of our hydroponic system was confirmation the effectiveness of the Dutch Bucket hydroponic method and floating farm platform that was adapted by groups in previous years of this project, as well as providing proof that the additions that were made to the system, such as the rain water collection system, perform efficiently and do not cause any problems to the system structurally. Furthermore, a study was conducted to consider alternatives for its potential use. The goal of this year of the project was to finalize the prototype of the floating farm hydroponic system, however future work includes turning over our system to groups that will implement this system in the Bahamas to test the effectiveness of the design in the location that it is intended to be deployed in. Furthermore, to effectively deploy hydroponic systems to address the correct issues on the topic of global food security and nutrition (GFSN), research and analysis needs to be done on all possible agricultural options to figure out the best solution. Additional expert input is necessary to determine the optimal location for implementing the unit. Due to the volume of data and labor needed to address these questions, it is outside of the scope of our project and will need to be addressed in future work.

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