Hydroponic Crop Cultivation as a Strategy for Reducing Food Insecurity

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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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Hydroponic Crop Cultivation as a Strategy for Reducing Food Insecurity*

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***Abstract*— Globally, coastal communities and Small Island Developing States (SIDS) are most at risk of food insecurity due to a variety of natural and economic factors [1]. Agricultural systems in these areas have a high level of exposure to climate risks including extreme weather and sea level rise [2]. The populations that are most vulnerable to the risk of food insecurity are lower-income, indigenous, rural, ethnic, and religious minority groups, as well as women and children [3]. Hydroponic Crop Cultivation (HCC) is a method of farming in which crops are grown in a nutrient rich solution in order to decrease the amount of resources, time, and space needed to grow. The project seeks to understand the role that HCC can play in mitigating risks to global food security and nutrition (GFSN) through three facets: 1) evaluation of the potential applications for HCC, including: SIDS, refugee camps, food deserts, rooftop gardens and apartment units, 2) ranking HCC against other technologies for GFSN risk mitigation, 3) build and test a floating, storm-resilient HCC system for the special case of GFSN in SIDS. The first two objectives will be ranked by a multi-criteria decision making (MCDM) method to determine the optimal use case while the last objective will be measured by the construction of a physical prototype. The system will use the Dutch bucket method of HCC to grow larger root crops, as well as enabling the functionality to grow multiple varieties of crops within the same system. The system will float in standing water and be able to withstand a reasonable amount of wind load, to allow the system to survive hurricanes. The HCC system relies on solar photovoltaic power to operate the HCC system, and will be designed to provide up to 72 hours of emergency power for communications and lighting. The functionality of the system will be assessed by testing in a calm water environment as well as simulations of wind loading.**

I. Motivation

Current food systems in place face pressure from population growth, demand for animal products, and availability of fertile soil as well as shifts in climate regimes. In the next century, climate change is projected to negatively impact the four pillars of food security – availability, access, utilization, and stability. Human induced climate change caused by carbon dioxide emission exacerbates 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 [4]. Small Island Developing States (SIDS) are located in the Caribbean, Pacific, Indian Ocean, and South China Sea and make up approximately 1% of the world's population. While far from homogeneous, small-scale farmers in SIDS face many of the same issues and are especially vulnerable to the impacts of climate change on food security. These populations face unique challenges due to their small land area, remote geography, and susceptibility to extreme climate events [1].

The goal of this project is to provide a humanitarian service of helping create sustainable food sources in Caribbean SIDS where there are frequent high risk natural disasters such as hurricanes and floods. Specifically, this project seeks to provide a template for 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. In order to determine what kind of system is best fitted to meet this need, a variety of alternatives were analyzed. This analysis justified the selection of a solar powered floating Dutch bucket hydroponics system. The justification for the selection of this system, its design, and a test of a prototype will be discussed.

II. Background

A. Climate Change

Caribbean SIDS are known to be small contributors to anthropogenic climate change however, they face a disproportionate amount of climate risk due to their size and location. The Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report sets out a framework for risk stating that it is determined by the "interaction between climate-related hazards and the vulnerability and exposure of both human and natural systems". Caribbean SIDS are especially vulnerable due to their close connection to coastal environments. 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 [5].

B. Food Security

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Agriculture plays a primary role in the economy of Caribbean nations. Haiti, Dominica, Guyana, and Grenada all have large agriculture sectors which contribute to 7%-17% of their respective total Gross Domestic Products. Despite their large production capacity of agriculture, most countries in this region are highly dependent on food imports [6]. Caribbean SIDS have greatly increased the amount of food imported into the region. Since 1990, the proportion of consumed food that is imported has risen from 40% to 60% with over half of countries importing over 80% of their food [7]. A higher reliance on imported food coupled with intensifying natural disasters due to climate change, adds volatility to markets and increases food instability.

C. *Current State of Agriculture*

Currently in the Caribbean, many rural households are small-scale farming operations or have some food production capabilities. These households often have a traditional attachment to the land and farming on it. Since these operations are independent, there is no larger small-scale farming system or organization in place [8]. Farmers in the region use a range of traditional methods like intercropping which is when two or more crops are grown within close proximity of each other with the goal of producing a greater yield of crops by utilizing resources that would not be taken advantage of by a single crop. This practice has numerous benefits such as erosion reduction, filtering pollutants from the soil, and slowing runoff [9]. Some small-scale farmers also use contemporary methods like greenhouse technology and organic farming to increase the value of their yield. However, many crop farmers also use agri-chemicals like fertilizers and pesticides which have been shown to harm the environment [8].

III. Selection of Use and Method of Farming

Surveys were created to quantify the selection process for both ranking farming technologies and finding the most competitive application of Hydroponic Crop Cultivation (HCC). Based on the background research, categories and criteria for evaluating each decision were created. Researchers reached out to experts in the field to participate in these surveys for more experienced perspectives.

Two different multi-criteria decision making (MCDM) methods, a simple dollar-value model and the Analytical Hierarchy Process (AHP), were compared to discover significant differences or consistencies between the two methods. In the simple MCDM model, participants were asked to distribute dollar amounts across categories, and subcategories within those categories, according to their perceived importance. Analysis was to be conducted using a simple rate and weight method, multiplying the category and subcategory weights by the rate assigned to an alternative for the respective subcategory. Neither simple survey received responses, so no analysis was performed.

The AHP, a MCDM approach derived by using sets of pairwise comparisons, was chosen to more robustly calculate criteria weights [10]. Participants expressed their opinions on the relative importance of criteria in pairwise comparisons, according to a defined scale. Two responses were received for the survey on ranking technologies, and none for the survey on ranking applications. One response concluded that HCC was the highest ranked technology (Fig. 1). The other participant did not complete the survey, stating that some components were "impossible to quantify without more info". Therefore, none of the surveys received sufficient results to draw definite quantifiable conclusions. This will be an item for future work on this project.

	Operation Cost	Yield Potential	Time to Harvest	Diversity of Crops
Access to Aerable Land	8.00	9.00	8.00	7.00
Access to Irregation Water	4.00	2.00	0.50	1.00
Access to Energy	1.00	1.50	1.00	0.13
Number of Workers	4.00	6.00	5.00	3.00
Education Level	6.00	7.00	8.00	8.00
Fixed Cost	1.00	3.00	4.00	4.00
Operation Cost	1.00	1.00	0.50	0.25
Yield Potential	1.00	1.00	1.00	0.50
Time to Harvest	2.00	1.00	1.00	1.00
Diversity of Crops	4.00	2.00	1.00	1.00
Income Increase	1.00	1.00	0.33	0.25
Personal Development	5.00	3.00	5.00	3.00
Ability to Survive Extreme Event	6.00	4.00	4.00	3.00

Figure 1. Analytical Hierarchy Process completed survey

Regardless of the results of the selection methods or lack thereof, this project was funded by a grant from the National Science Foundation to design and build a HCC unit capable of producing supplemental food supply in SIDS. This project therefore focused on said combination when creating the floating platform design.

IV. Related Research

The premise of this project relied heavily on the past research and experiments done in the field. This section will highlight two instances of floating agriculture systems that were used as inspiration for the final design of the system as well as a brief introduction to the Dutch bucket hydroponic method.

In Bangladesh, farmers have been creating floating farms out of local organic materials for over 300 years. The technique includes harvesting weeds such as water hyacinth to construct a raft and planting seedlings in the organic beds [11]. Due to climate change, floating farms are now a critical component for providing farmers with a sufficient food supply and income. Another instance of the floating farm concept can be found in Rotterdam, Netherlands where a floating dairy farm opened in May of 2019. The farm intends to alleviate concerns about rising sea levels affecting availability of farmland by farming cattle on the harbor. The structure can withstand the harbor's 8 foot tides without tilting more than 11 inches, even in 70 mph winds [12].

The Dutch bucket method is a type of hydroponics which uses individual pots or buckets to grow plants. In this system, the buckets are filled with a growing medium such as pearlite or coconut husks with a layer of clay pellets on the bottom to assist with drainage. The pots are positioned along a pipe or similar water distribution system which distributes a nutrient solution from a central reservoir to each bucket. The water can then either be drained or circulated back into the system.

V. System Design

The system design balances microgrid power capability, wind and flood resistance, and reasonable protection against pests and rainwater intrusion. These priorities were specified by the client and previous work. An 8 by 8 foot square platform supports a Dutch bucket hydroponics system and electrical equipment. Trapezoidal storm doors fold to 45 degrees, creating a protective shell around the electrical and hydroponics systems, maximizing vertical space while minimizing wind stress on the structure (Fig. 2, 4). Storm doors open to expose (4) 100-watt photovoltaic (PV) modules (Fig. 3, 4). A central tower provides structural support and houses the electrical system. The platform is positively buoyant using closed-cell foam, designed for 35% submergence. The remainder increases freeboard for wave action.

The electrical system is designed to provide electricity to hydroponics, communications, refrigeration and lighting systems for up to 72 hours with no solar gain. PV power input is regulated by a charge controller and energy storage is provided with a 100 amp-hour battery, while an inverter provides 110-volt AC power for auxiliary loads.

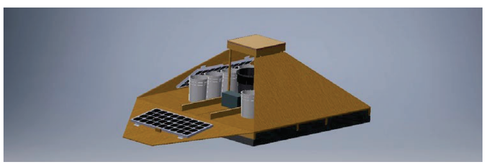

Figure 2. Floating platform AutoCAD model, partially folded.

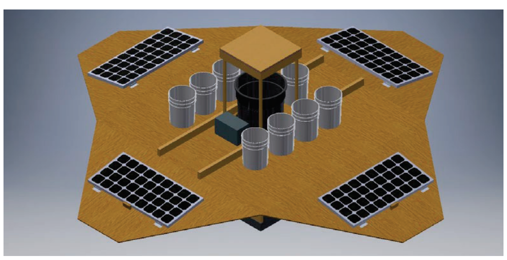

Figure 3. Floating platform AutoCAD model, unfolded.

Figure 4. Prototype floating platform, partially folded.

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.

Electrical: The electrical design criteria is 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.

B. Costs

The prototype Dutch bucket system was constructed prior to the Floating HCC Platform as a proof of concept for the Dutch bucket method, and cost a total of $420.37. The Floating HCC Platform cost a total of $812.72, not including the cost of electrical equipment which was reused from previous work. Our initial cost estimate for the Floating HCC Platform, including all new electrical equipment, was $1617.00. The majority of costs for the Dutch bucket prototype were in crop containers and fittings, whereas the majority of cost for the Floating HCC Platform was in lumber, flotation foam, and crop containers.

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. The 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 would reinforce wind forces on the structure. Our values are preliminary and may be updated once construction is complete. We recommend that the system be anchored to prevent loss or damage.

D. Dutch Bucket System

The Dutch bucket system (Fig. 5) was created using 2-gallon buckets filled with perlite and clay pellets as a medium to hold the crops. Tubing is suspended over the top of the buckets with nozzles to deliver the nutrient solution to the plants for fifteen minutes every two hours. The nutrient solution is circulated by a pump in the reservoir. Each bucket is fitted with a drain tube that allows water to drain using gravity and flow back into the water reservoir. Initially, small grains of perlite clogged some of the drains causing the system to overflow or have decreased circulation. This issue was remediated by installing screens in front of the bucket drains to prohibit perlite from leaving the buckets and clogging the drain tubes.

Figure 5. Dutch bucket system.

To test the Dutch bucket prototype system, four crops were chosen based on their similar nutrient needs, availability from the local gardening store, and diversity of produce: lettuce, brussels sprouts, broccoli, and basil. The plants selected needed to have similar nutrient requirements since the HCC system circulates from one basin of water. Due to time constraints (waiting for warmer weather to plant because the system is outdoors), seedlings were used to demonstrate proof of concept for the Dutch bucket system. Two buckets were dedicated to each crop. Three seedlings of brussels sprouts and broccoli were placed in their respective buckets while the buckets containing lettuce had four seedlings due to their small size. Finally, the basil plants had one plant per respective bucket. Over the course of three weeks, the plants have grown and appear to be healthy, although the basil plant has shown some yellow spotting, probably a sign of nutrient deficiency. After increasing the nutrient solution in the water basin, all plants are growing and thriving. Because of the time constraint, the brussels sprouts and broccoli have not yet come to fruition and will likely produce vegetables in another 60 days or so. The plants should continue to grow into late spring and summer and eventually produce edible crops.

VI. Conclusions and Future Work

The result of this capstone project is a proof of concept of the Dutch bucket hydroponic method as well as a prototype of the designed floating farm platform. While this project separately created both the floating platform and the Dutch bucket hydroponic system, the two components were not integrated. This will be the focus of future work. Additionally, further analysis is required on whether the design can withstand exact hurricane conditions respective to Caribbean SIDS. Under terms of the NSF grant future work includes implementing this system in Abaco Island of the Bahamas as a case study of its feasibility in the local context of SIDS.

Finally, for broader consideration of the role of HCC systems in addressing global food security and nutrition (GFSN), a thorough evaluation of the potential applications of HCC such as in SIDS, refugee camps, food deserts, rooftop gardens and apartment units is required. This will be accompanied by a ranking of HCC against other technologies such as conventional crop cultivation in the ground, aquaponics, and indoor controlled environment agriculture in greenhouses. This analysis to match the appropriate food production technology to a given GFSN application will use data from extensive literature reviews and surveys of experts that was beyond the scope of our project.

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