YIELD EFFECTS OF WATER DEPTH ON LETTUCE GROWN IN HYDROPONIC CHANNELS

A Research Report

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by

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Abstract

Hydroponically grown lettuce has been a staple crop in CEA (Controlled environment agriculture) facilities for decades, however, there is still knowledge to be discovered on how to grow most optimally. There are a handful of system designs that have been optimized for growing lettuce and other greens such as NFT (Nutrient Film Technique), DWC (Deep Water Culture), and aeroponics. Many of the parameters that differ among the types of hydroponic systems are well understood in regard to growing lettuce. However, there seems to be little information on the effect of changes in water depth in nutrient film technique (NFT) channels and how that may affect plant growth. As suggested by the name, NFT systems employ a thin layer of recirculating nutrient solution in which the root plants grow. However, it is unknown whether a deeper water column in the same channels will affect yield. A deeper column may also help mitigate detrimental effects of temporary pump/power outages. The objective of this study was to discern whether changes in water depth in NFT channels would have an effect on the growth of lettuce (*Lactuca sativa*), ’Rex’. Lettuce was grown in a greenhouse in prefabricated plastic channels at four different water depths (0.3 cm [control, standard NFT water depth], 0.5 cm, 1.0 cm, 2.0 cm). The system was designed so that the water depth was the main variable between treatment groups. Over the course of three crop cycles, information on plant biomass (fresh and dry weights of the roots and shoots, root-to-shoot ratio) and morphological cylindrical volume was determined. Changes in water depth led to significant changes in dry weight, but not in fresh weights. Specifically, mean root dry mass from the 0.3 cm group was significantly greater (from 5.9% to 6.2% increases) than the other treatments. Mean dry weight of lettuce heads in the 0.3 cm was also significantly higher (3.1% increase) than the 2.0 cm treatment. In regard to cylindrical volume, the 0.3 cm control treatment had an overall lower mean volume (12.4% decrease) compared with the 2.0 cm depth treatment. There were no significant differences between treatment for fresh weights of the roots or shoots or the root-to-shoot ratio. Overall, based on fresh weight, a deeper water column could be employed in NFT systems to mitigate temporary power outages, to save on energy costs, or take advantage of other design benefits; though more research should test these notions in a commercial facility.

Biographical Sketch

Connor John Schmitz was born in January 1992 and grew up in Ronkonkoma, New York. He was always interested in how the natural world operates and thus studied Ecology at the State University of New York at Plattsburgh. Although he was mostly interested in wildlife ecology at the time, his foray into an eventual career in agricultural research was seeded from the overwhelming number of discussions that regarded agricultural practices as an agent of sometimes catastrophic change in ecological systems. He graduated with a bachelor’s degree in 2016.

After graduating, he decided to spend the summer working on a farm in the Adirondack Mountains of New York where he first worked with commercial hydroponic systems. While there, he applied to the US Peace Corps and thereafter spent over two years volunteering in a small community in Nepal as an agriculturalist, introducing the community to new vegetable and fruit cultivars (most notably kiwifruit) and various topics such as fruit tree cultivation, mushroom cultivation, grafting, composting, basic nutrition, and women’s health. He learned, among much else, that agricultural methods involving less technology did not inherently account for a net positive benefit to ecological health in a natural system.

From a young age, Connor was always interested in technology. It wasn’t until his experience in Nepal that he decided to focus on this passion and applied it to understanding technology in agriculture. He applied for and was accepted to Cornell University’s Masters of Professional Studies in Controlled Environment Agriculture (CEA), hoping to hone his knowledge and skills regarding plant science and technology in agriculture.

He believes that medium-sized CEA facilities that cater to truly local markets are an undervalued socio-agricultural agent that can help support and benefit the surrounding natural environment while at the same time cultivating an important connection between people, their farmers, and ultimately, their food.

Acknowledgements

I am honored to be able to thank Dr. Neil Mattson, my program advisor and professor, for his wisdom and guidance during my time at Cornell. My background was not necessarily catered to an academic environment, and I have felt blessed to have had such a genuine and knowledgeable advisor and professor. Aside from so much he taught me regarding CEA, I hope to one day exercise the humility, patience, and leadership he exudes on a daily basis.

Secondly, I would like to thank the Cornell CEA lab and greenhouse staff. Without the guidance and vast experience of the research support specialists Nicholas Kaszmar and Kendra Hutchins of the CEA lab, my transition back into an academic environment would have been much more challenging. You further taught me to not only utilize and appreciate human resources that are available to me, but to also trust in my own judgement and find confidence in my decision-making.

Thirdly, I wanted to say thanks to all the people in the Office of Professional Programs who make possible the M.P.S. programs at Cornell, specifically Tara Reed and Marvin Pritts. As stated previously, as an attendee returning to academia, I felt the program was a perfect fit for my needs and I wouldn’t change much about it. The guided freedom and opportunity of a focused exploration was an integral part of my confidence building, understanding of the field, and ultimately steered me towards a specific heading, on course to what excites me most about the field as a whole.

Finally, I wanted to thank my family and friends. Without their never-ending support, I’d have not strode for the heights I have.

Table of Contents

List of Figures

List of Tables

List of Abbreviations

CEA – Controlled Environment Agriculture

NFT – Nutrient Film Technique

DWC – Deep Water Culture

SWC – Shallow Water Culture

RH – Relative Humidity

SD – Standard Deviation

HRT – Hydraulic Residence Time

Introduction

Controlled Environment Agriculture (CEA) is the scientific approach of engineering and maintaining optimal growing environments for crop production and research, on earth, and beyond.

CEA includes manipulating parameters such as soil or soilless media type, humidity, lighting, temperature, fertilizers and nutrients, and carbon dioxide concentration; just to name a few (Walters, 2020). These tools allow for growers in nearly any place on earth, and more recently in earth's orbit, to achieve environmental conditions that are optimal to plant growth.

CEA is focused on controlling the environment within a structure. This can include greenhouses, warehouses, homes, or space stations. One of the most important aspects of controlling a plant's environment is catering to a healthy root culture. Soil's popularity as an indoor growing substrate has dwindled since the 1920s (Hoagland and Arnon, 1950). For greenhouse and other indoor growers, hydroponics started to become the preferred method of growing.

Hydroponics is described as the method of growing agricultural crops in a soilless root culture zone. This method of growing utilizes a liquid root culture zone or soilless media such as perlite, vermiculite, expanded clay pebbles, peat, bark, rockwool, coconut husks; or a mixture of any of the aforementioned materials (Walter, 2020)

There are plentiful reasons a producer would choose to grow crops hydroponically. For example, if water is scarce, growing hydroponically can assist in saving water. Hydroponic growing media, such as rockwool, tends to have better drainage and can mitigate root diseases and buildup of salts (Jensen, 1997). Although growing hydroponically does not inherently lead to better crop yields, a knowledgeable grower can optimize the aerial and rhizosphere environment more exactly to realize the plant's fullest growth potential by providing for an optimal environment (Hoagland & Arnon, 1950).

There are a handful of popular hydroponic systems that are in use today. Nutrient Film Technique (NFT), Deep Water Culture (DWC), Drip-to-Drain, and Aeroponics are some of the more popular forms of hydroponic growing.

Studies have shown that NFT systems and DWC systems often yield similar results in regard to yield data such as fresh weight (Walters and Currey, 2015). This is key to the present study, as the water column depth is being observed, rather than type of hydroponic system.

NFT systems utilize plastic channels that are raised on one end to provide a slight grade that water gradually flows down. The water that flows down the channel forms a "film" of nutrient solution that is then taken up by roots of plants that are placed in the channel. The nutrient solution drains into a reservoir and this is recirculated back to the channels. Most commonly, the seed is sown in rockwool cubes and then the seedlings are transplanted in the NFT channels at the 3-4 true leaf stage. With proper maintenance, this system is a very viable way of growing short-statured plants, most especially for crops such as leafy greens and herbs (Burrage 1993; Mohammed and Sokoo, 2016).

Deep Water Culture Systems are unlike NFT systems in that the roots of the plants are suspended in a reservoir filled with nutrient solution. Generally, this is achieved by suspending a plant over water via a floating raft and submerging the roots in water. Generally, DWC systems utilize a root culture zone ranging from 6 to 8 in or greater (Hoagland and Arnon, 1950: Brechner and Both, 2013). This is another viable way to produce crops, most commonly for lettuce and herbs.

There are other types of hydroponic systems that utilize a growing media rather than growing roots in water, but this study was focused on liquid root culture zones.

Both of the aforementioned systems are well studied, however, more information regarding alternative concepts or hybrid forms of hydroponic systems may lead to a beneficial outcome. Understanding various forms of systems and the parameters that differ between them can help make the technology more easily adoptive for different circumstances and environments, whether limiting agents are by nature financial, environmental, or cultural.

One of the issues with NFT systems is that in specific situations, it is not ideal to have only a thin layer of water to protect the roots from drying out. For example, in an area that experiences frequent power outages. If the power supply is terminated, the water around the roots stops being replaced and due to the gradient of the NFT channel, the water quickly flows away from the roots and exposes them to air and ultimately drying quickly, potentially harming the plant. Having a deeper water depth may help curb some of these specific issues. However, the effect of channel depth on plant productivity has not been well-studied.

Another benefit of having a more voluminous reservoir for the roots to grow in is a potential energy savings in regard to the water pumping mechanism. In an NFT system, the pump is generally on constantly, so the roots always have access to a continual flow of water. However, this can add to the expenditures of the business. By having a deeper water column, it may be possible to intermittently power the pump and only replace the water in the channels when needed, potentially saving on energy expenses.

The objective of this study was to determine the impact of channel nutrient solution depth on yield of head lettuce.

Materials & Methods

To understand the effect of water depth on hydroponically grown lettuce, a recirculating hydroponic system was designed to limit and control the variability of the environment. For this reason, water depth was manipulated within homogenous plastic channels (NFT channels).

The study took place at Cornell University's Guterman Bioclimatic Laboratory, located in Ithaca, NY, USA (42.44, -76.45).

The NFT channels were manufactured by HydroCycle. Twelve were purchased and shipped by FarmTek (South Windsor, CT, USA). The channels were 6 ft (1.82 m) long, 4 in (10.16 cm) wide, and 2 in (5.08 cm) deep. Water was circulated from a 40 gal (151 L) reservoir through an inline mesh strainer and emitted into the channels from barbed fittings through spaghetti tubing. The average flow rate through the channels were 26.4 $L \cdot h^{-1}$ (440 $cm^3 \cdot min^{-1}$) with a std. dev. of 1.7 $L \cdot h^{-1}$. The average approximate hydraulic residence time (HRT) in each channel of each treatment was calculated and can be seen in Table 1.

$$Equation.1 \mid Approx.HRT = \frac{Water\ Depth * Channel\ Length * Channel\ Width}{Average\ Flow\ Rate}$$

Table 1. Hydraulic residence time (HRT) in hydroponic channels based on water depth treatment.

Treatment	Approx. Hydraulic Residence Time
0.3 cm [NFT]	1.26 minutes
0.5 cm	2.10 minutes
1.0 cm	4.20 minutes
2.0 cm	8.41 minutes

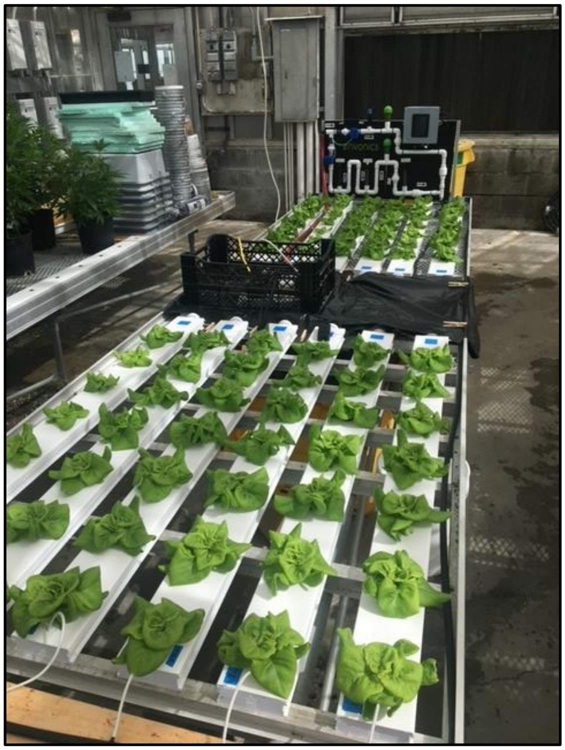
Table 2. Nutrient concentrations of fertilizer used in this study, as described by Mattson & Peters.

Element	ppm
Nitrogen (N)	150
Phosphorus (P)	39
Potassium (K)	162
Calcium (Ca)	139
Magnesium (Mg)	47
Iron (Fe)	2.3
Manganese (Mn)	0.38
Zinc (Zn)	0.11
Boron (B)	0.38
Copper (Cu)	0.113
Molybdenum (Mo)	0.075

The electrical conductivity (EC) and pH was monitored and adjusted approximately every one to two days, until an automated pH controller was implemented during the third crop cycle when only the EC was monitored manually. 100x stock concentrates of fertilizer were prepared by mixing 284g each of Jack's 5-12-26 hydroponic fertilizer and Yara's 15.5-0-0 CalciNit Greenhouse grade fertilizer, separately, in 1 gal of reverse osmosis water. These concentrates were then diluted to provide the plants with a nutrient solution concentration as described by Mattson & Peters (2014) and in Table 2.

The EC of the reservoir was maintained at a range of 1.6-1.8 throughout the experiment. The pH was monitored and maintained manually during the first two crop cycles. When pH was found to have exceeded 6.0, 1 M sulfuric acid was carefully added to the reservoir to maintain a pH range of 5.56.0. During the last crop cycle, an Arduino microcontroller was implemented, and pH was automatically maintained in a range of 5.6-6.0 by dosing 1 M sulfuric acid when rose above 6.0.

Water depth was manipulated by using 1" PVC elbows attached to 1" PVC unions at the end of the channels, as shown in the photos below. The water depth was easily manipulated by changing the direction of the elbow (upward to raise water height).. This system was designed so water depth could easily be changed and randomized throughout the study.



Depths of 1.0 cm and 2.0 cm were marked with a permanent marker at the exit of the inside of the channel and the PVC fittings were manipulated until the water depth was at the level of the mark within the channel. When the channel exit was not manipulated to increase the water depth, the inherent water depth in the channel was 0.5 cm. To achieve the water depth of 0.3 cm (control, standard NFT channel depth), the channels of this grouping were lifted slightly on one end, effectively mimicking an NFT system. The channels were then labeled (0.3 cm, 0.5 cm, 1.0 cm, 2.0 cm) with tape and location noted.

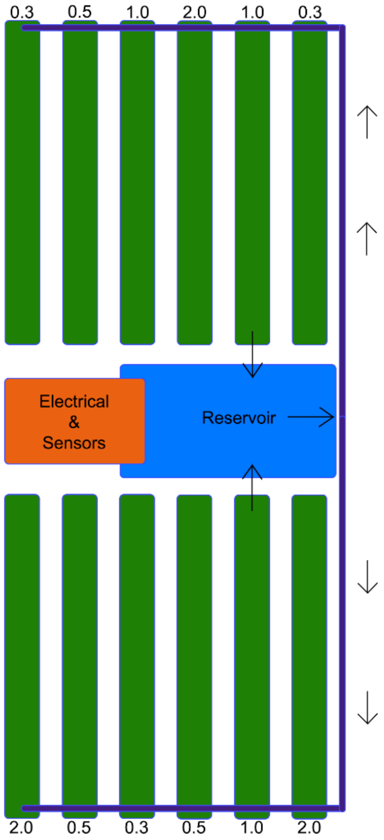


Figure 1. Diagram of experimental design. Numbers at the end of the green rectangles represent the treatment group. For every crop cycle, the layout was not repeated.

In regard to research design randomization, the depth of each channel was pre-determined for each crop cycle so that treatment applied to the a given channel for one crop cycle was not applied channel took up would not be used again for the same treatment throughout the project, while subsequent channels were dissimilar (Figure 1). However, because only three crop cycles were used for analysis, not every possible variation was utilized. This resulted in an incomplete block randomization design.

Lettuce 'Rex' seeds were sown in 1" rockwool cubes and fertilized with 21-5-20 fertilizer applied at 150 ppm N. Seedlings were randomly selected and transplanted into the hydroponic system after two weeks when seedlings had 4 true leaves. Lettuce was grown for three weeks after transplanting during which time treatments were applied, for a total of five weeks from seeding to harvest. Environmental parameters in the greenhouse are noted in Table 3.

Table 3. Environmental parameters [RH, T, and DLI], for each crop cycle.

	Crop Cycle 1 6/24-7/28	**Crop Cycle 2 7/08-8/12**	**Crop Cycle 3 8/05-9/09**
Relative Humidity (%)	Max: 86.7 Min: 39.2 Average: 67.6	Max: 86.7 Min: 35.0 Average: 68.2	Max: 92.9 Min: 41.9 Average: 73.3
Temperature (°F)	Max: 94.6 Min: 63.8 Average: 76.3	Max: 89.9 Min: 59.3 Average: 75.2	Max: 93.1 Min: 58.7 Average: 74.6
DLI (mol/m^2/day)	Average: 20.35	Average: 20.65	Average: 17.51

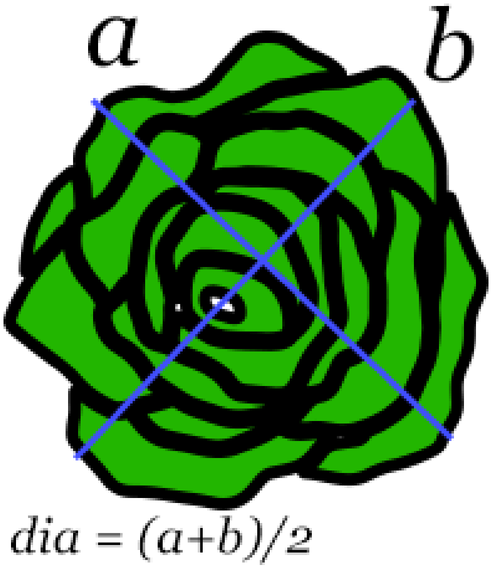


Figure 2. Diagram depicting how the diameter for use in figuring the cylindrical volume of the lettuce was obtained.

Before harvesting at five weeks after sowing, a ruler was used to measure the mean diagonal diameter of each plant, leaf tip to leaf tip, as shown in figure 2.

Heights were also recorded before harvest, and from these parameters cylindrical volume measurement was assessed using the calculation below.

$$Equation\ 2. \mid \pi \left[\frac{a+b}{4}\right]^2 \times h$$

Plants were then cut at the stem just above the top of the rockwool cube, weighed for fresh weight, and then placed into labeled brown bags for drying in the oven. After all lettuce was cut, weighed, and placed into individual bags; the tops of the channels were removed. The roots of the plants, along with the rockwool cubes, were then removed from the channels. Since the roots of individual plants had grown together within the channels and separating them on an individual plant basis was impossible, roots from entire channels were removed and assessed as a single unit. After removal, the water was drained with a light compression by hand until water no longer dripped from the root mass. Fresh weight was recorded, and thereafter placed within brown bags for drying.

The samples were dried at 70° C (158 °F) for approximately 72 hours in a drying oven to ensure the shoot and root masses were completely dry. Thereafter, an average empty bag weight was weighed, samples were weighed within the bags, and the weight of the bag was then subtracted, leaving the dry weight of the sample, which was recorded in an excel file.

‘Root to shoot’ ratios were calculated by dividing the shoot dry weight by the root dry weight, and thereafter analyzed.

The experiment was designed as an incomplete block randomized design with 3 replicate channels per treatment condition for each of three replicate crop cycles (block). Analysis of variance and other statistical analysis was conducted in (RStudio [RStudio, Boston, MA], JMP Pro [SAS Institute Inc., Cary, NC], and Excel [Microsoft Corporation, East Syracuse, NY]) to determine the impact of treatment, crop cycle, and their interaction for each of the examined parameters. Where treatment differences existed, Tukey's Honestly Significant Difference (HSD) was used to determine significant differences between treatment.

Results

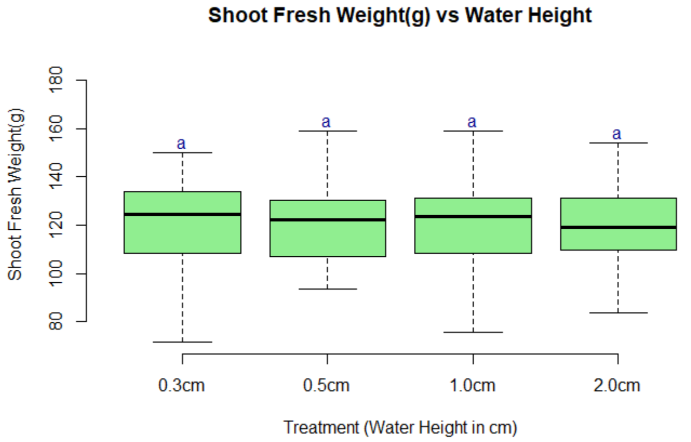
Lettuce Head Fresh Weight

According to ANOVA analysis as seen in Table 4, there was no significant interaction (p = 0.93) between the treatments and crop cycle. However, fresh weight significantly differed by crop cycle, with the third cycle having the lowest weights.

Table 4. Two-way ANOVA: Lettuce head fresh weight vs treatment and crop cycle.

Source	DF	Sum of Squares	F Ratio	Prob > F
Treatment	3	117.5	0.15	0.93
Crop Cycle	1	6056	23.51	<.0001*
Treatment*Crop Cycle	3	1398	1.81	0.15

According to ANOVA analysis as seen in Table 4, there was no significant interaction (p = 0.93) between the treatments and crop cycle. However, fresh weight significantly differed by crop cycle, with the third cycle having the lowest weights.



Level		Least Sq Mean
0.3cm	A	121.5
2.0cm	A	121.0
1.0cm	A	120.7
0.5cm	A	119.7

Figure 1 and Table 5. Boxplot depicting the shoot fresh weight vs treatment groups and the respective Tukey's HSD analysis.

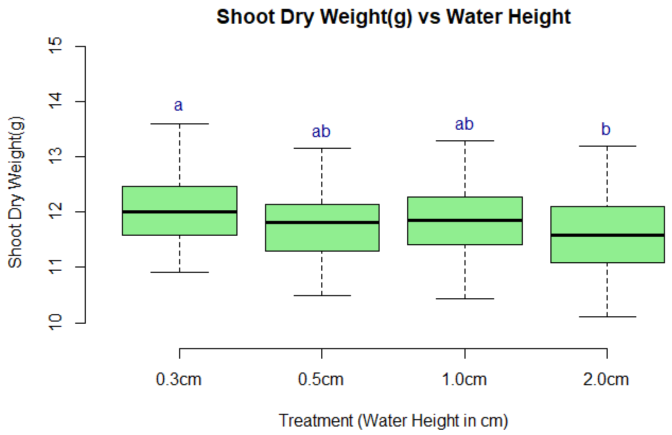
Fresh weight of the lettuce heads ranged from 71.8 g to 176.0 g, with a study-wide mean of 120.7 g. The 0.2 cm group had the greatest plant to plant variability (standard deviation [SD] of 18.86 g, while the 0.5 cm water depth treatment had the lowest SD of 15.41 g. Based on Tukey's HSD model, there was not significant difference between the treatments (Table 5).

Lettuce Head Dry Weight

According to the ANOVA test, there was a significant difference between treatments (p = .029), as well as crop cycle (p = .0002, Table 6).

Table 6. Two-way ANOVA: Lettuce head dry weight vs treatment and crop cycle.

Source	DF	Sum of Squares	F Ratio	Prob > F
Treatment	3	4.14	3.05	0.0294*
Crop Cycle	1	6.41	14.13	0.0002*
Treatment*Crop Cycle	3	0.899	0.66	0.58



Level			Least Sq Mean
0.3cm	A		12.00
1.0cm	A	B	11.79
0.5cm	A	B	11.77
2.0cm		B	11.65

Figure 4 and Table 7. Boxplot depicting the shoot dry weight vs treatment groups and the respective Tukey's HSD analysis.

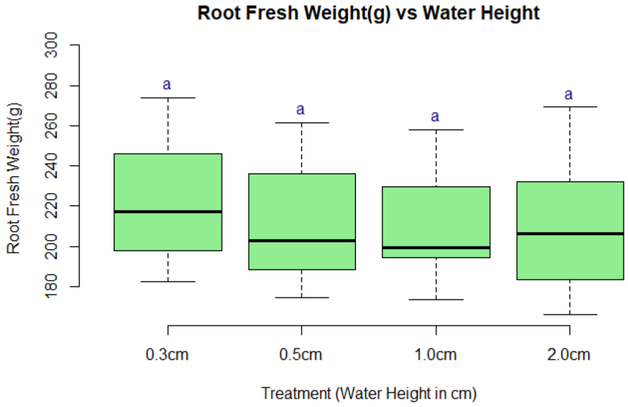
Overall, the dry weights of lettuce ranged from 9.75 to 13.60 g. The 0.5cm water depth treatment had the lowest SD over the course of the experiment, while the 1.0 cm water depth had the greatest SD. The 2.0cm water depth treatment was significantly different from the 0.3cm group, resulting in a median decrease of approximately 3%, while neither the of the other treatments were significantly different from either the 0.3 cm group or the 2.0 cm treatment group (Figure 4, Table 7).

Root Fresh Weight

There was a significant difference between results on a crop cycle basis regarding fresh root weight (p = .0001, Table 8) with the first crop cycle having the highest weight, and generally decreasing with each subsequent crop cycle.

Table 8. Two-way ANOVA: Root fresh weight vs treatment and crop cycle.

Source	DF	Sum of Squares	F Ratio	Prob > F
Treatment	3	561.69	0.98	0.41
Crop Cycle	1	28495.66	149.86	<.0001*
Treatment*Crop Cycle	3	254.04	0.45	0.72



Level		Least Sq Mean
0.3cm	A	220.94
2.0cm	A	212.32
1.0cm	A	211.94
0.5cm	A	211.31

Figure 5 and Table 9. Boxplot depicting the root fresh weight vs treatment groups and the respective Tukey's HSD analysis.

The fresh weight of the roots ranged from 166.25 g to 273.95 g. The 2.0 cm water depth treatment had the greatest SD of 37.77, while the lowest SD was recorded from the 1.0 cm water depth treatment. There were no significant differences in root fresh weight based on treatments (Table 8, Table 9).

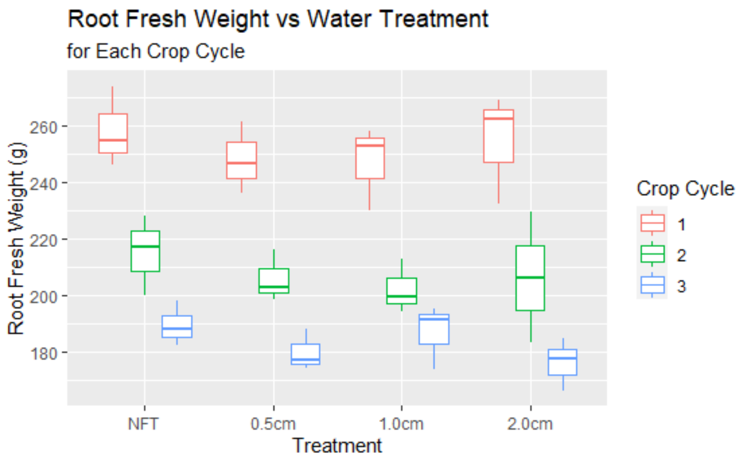


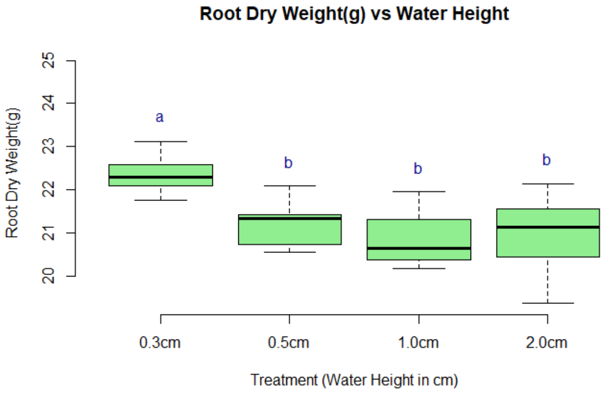
Figure 6. Boxplot depicting the fresh weight of the roots vs treatment groups between crop cycles.

Root Dry Weight

According to the ANOVA analysis, root dry weights were significantly different between treatments (p = .0068, Table 10).

Table 10. Two-way ANOVA: Root dry weight vs treatment and crop cycle.

Source	DF	Sum of Squares	F Ratio	Prob > F
Treatment	3	10.47	4.98	0.0068*
Crop Cycle	1	0.48	0.68	0.42
Treatment*Crop Cycle	3	1.03	0.49	0.69



Level			Least Sq Mean
0.3cm	A		22.24
0.5cm		B	21.06
1.0cm		B	20.98
2.0cm		B	20.94

Figure 7 and Table 11. Boxplot depicting the root dry weight vs treatment groups and the respective Tukey's HSD analysis.

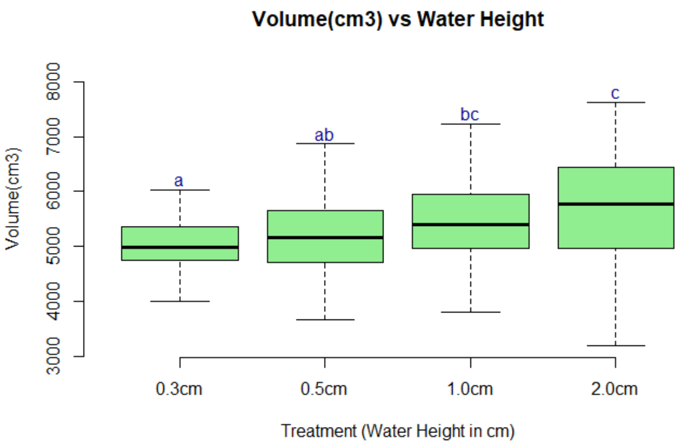
Dry weights of the roots ranged from 19.35 g to a maximum of 23.11 g throughout the course of the experiment. The 0.3 cm group had the lowest SD of 0.63, while the 1.0 cm treatment group had the maximum SD at 0.93. The 0.3 cm group showed a significantly higher dry root weight compared to the other treatment groups (Figure 7, Table 11)**.**

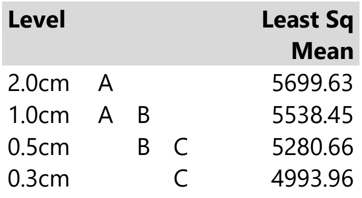
Cylindrical Volume

A two-way ANOVA found that there was significance between the treatment groups, the crop cycle, as well as the interaction between the treatment groups and the crop cycle (Table 12).

Table 12. Two-way ANOVA: Cylindrical volume vs treatment and crop cycle.

Source	DF	Sum of Squares	F Ratio	Prob > F
Treatment	3	18027846	10.92	<.0001*
Crop Cycle	1	36077949	65.55	<.0001*
Treatment*Crop Cycle	3	6777106	4.10	0.0073*





Level				Least Sq Mean
2.0cm	A			5699.63
1.0cm	A	B		5538.45
0.5cm		B	C	5280.66
0.3cm			C	4993.96

Figure 8 and Table 13. Boxplot depicting the cylindrical volume vs treatment groups and the respective Tukey's HSD analysis.

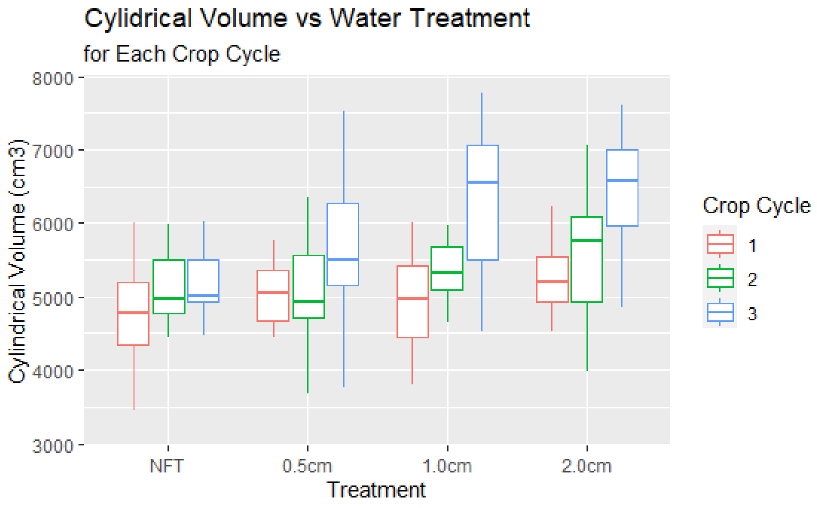


Figure 9. Boxplot depicting the cylindrical volume vs treatment groups between crop cycles.

To further understand why this had occurred, the data was broken down into multiple boxplots and groups were delineated based on which crop cycle the data was harvested from, as depicted in figure 9.

The cylindrical volumes ranged from 3200 cm^3 to a maximum of 7774.74 cm^3. Median volume showed an increasing pattern of 4983.18 cm^3 to 5762.39 cm^3 as water depth increased from 0.3 to 2.0 cm. The highest SD was recorded from the 2.0 cm water depth treatment group at 1000.89, while the lowest recorded was from the 0.3 cm group at 650.36. The 0.3 cm group had significantly smaller volume than the 1.0 cm and 2.0 cm water depth treatment group, while the 0.5 cm group was significantly smaller than the 2.0 cm group. The median of the 0.3 cm group was 13.5% smaller than the median of the 2.0 cm water depth group.

Root to Shoot Ratio

The root to shoot ratios were not significantly impacted by treatment (p = 0.38, Table 14). The SD of the ratio was highest in the 1.0 cm group (0.12), and lowest in the 0.3 cm group (0.07).

Table 14. One-way ANOVA: Root to shoot ratios vs treatment.

Source	**DF**	**Sum of Squares**	**Mean Square**	**F Ratio**	**Prob > F**
Treatment	3	0.03	0.009	1.07	0.38
Error	32	0.28	0.009		
C. Total	35	0.30			

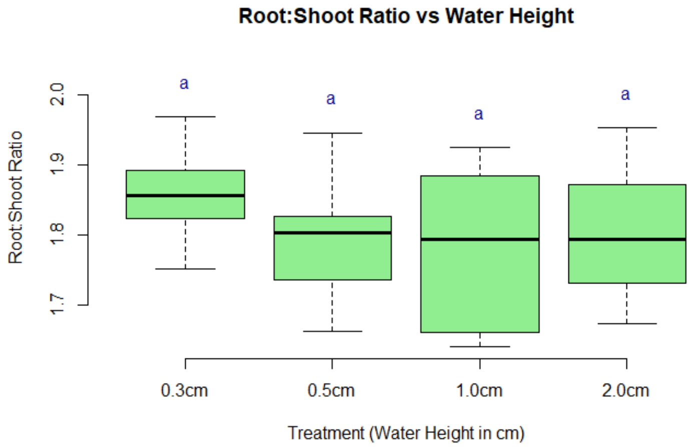


Figure 10. Boxplot depicting the root to shoot ratios vs treatment groups.

Discussion

Fresh Weights

Water depths ranging from 0.3 cm to 2.0 cm did not affect the fresh weights of Rex lettuce heads in the current study (Figures 3 & 5). However, using water depths commensurate to what is used in an NFT system may result in greater plant to plant variability in head fresh weight. The most uniform lettuce heads were achieved in the 0.5 cm treatment group.

Both the fresh weight of the shoot and the roots were significantly impacted by crop cycles (Tables 4 & 8). This may have been a result of a changing greenhouse environment throughout the course of the research. For example, the lower average DLI of the last crop cycle coincides with the lower fresh and dry weights (Table 3). However, by design, each crop cycle contained 3 replicate channels per treatment condition and thus relative differences should hold. This can be seen in that, aside from the cylindrical volume, there was no significant interactions between the crop cycles and the treatment groups (Tables 4, 6, 8, & 10). The discrepancies between crop cycles may have been due to the change from completely manual water quality control to the implementation of a microcontroller and peristaltic dosing pump for pH control. Although no data was recorded for analysis regarding the pH, it can be noted that the pH was seemingly in more accurate and precise control when the microcontroller was implemented. Related to the automated pH control, it would be interesting in future experiments to test the benefits of keeping pH constant or letting it fluctuate within a range.

Root fresh weights also differed between crop cycles (Table 8). The method used was to remove the roots from the channels, squeeze excess water out by hand, and then weigh the root mass. This left room for human error especially between crop cycles, which were conducted weeks apart. The exact pressure that was exerted on the roots could have varied between not only crop cycles, but also on an individual and treatment basis. However, best effort was made to reproduce the methodology and it could be that root fresh weight differed between crop cycle due to other environmental variables.

Dry Weights

Water depth impact dry biomass accumulated by heads and roots of ‘Rex’ lettuce (Table 6 & 10) in the current study. In terms of dry biomass, the 0.3 cm group was significantly more productive than the other groups when analyzing both the shoot and root data (Figures 4 & 7). Since the roots are not inherently suspended in the nutrient solution like the other treatment groups, it is logical to think that the plant roots may compensate by growing a larger root system to access the required nutrients. Interestingly, the energy invested in this process of root growth did not seem to negatively impact the growth of the plant.

Dry root weights were highest in the first crop cycle. This may have been, again, due to differences in pH control. Anderson et al. (2017) reported that maintaining a pH value of 5.8 decreased both the dry and fresh weight of the roots opposed to treatments that maintained a higher pH of 7.0, regardless of the effects this had on overall plant quality and growth. This aligns with the assumptions about pH control in this study, since the third crop cycle was kept at an average of approximately 5.8. It can be assumed then that less favorable root culture environments trigger a process that subsequently led to higher root mass.

Volume

Capturing accurate measures of volume of live plants is a difficult feat. In this study, height and diameter measurements were used to estimate volume of the plant as a cylinder.

However, it should be noted that this method was subject to human error. Especially regarding different crop cycles, which took place weeks apart from each other. In future studies using a more accurate approach, such as water displacement, may yield more accurate/precise results. Since the interaction between crop cycles and treatment was significant in this study (Table 12), it may be that there were either inconsistencies in measurement method or that there were real differences due to changing environmental conditions during crop cycle.

There was a negative correlation between lettuce head volume and the root dry weight. For example, although the third crop cycle grew larger plants by volume compared to the other crop cycles, the third crop cycle grew less root mass (Figures 6 & 9).

System Design

Hydraulic residence time in the channels differed based on the treatment (Table 1). It was assumed that dissolved oxygen would not be a limiting factor in this study, however, in future studies this metric would be important to track. In the 2.0 cm treatment channel, for example, the residence time was approximately 8.4 minutes. Depending on the needs of the plant, this may have affected the results if the oxygen was depleted in that time. However, without taking DO measurements, it is impossible to say. It is unknown whether or not dissolved oxygen had an effect on the growth of the lettuce. One benefit to using NFT systems is that the roots are more easily exposed to oxygen, and the 0.3 cm group mimicked an NFT system, while the other groups mimicked a hybrid NFT and shallow water culture system. Subsequent work should quantify dissolved oxygen concentration.

Conclusions and Closing Remarks

To our knowledge, this experiment represents the first attempt to investigate the impact of channel nutrient solution depth on plant performance of lettuce. Overall, water depth did not impact plant fresh weight but did impact volume and dry weights. Because no reductions in fresh weight were found with increasing water depth, this might be considered a viable technique in commercial systems which would provide a greater buffer of nutrient solution should pumps/electricity fail, opposed to traditional NFT systems. Increasing water depth led to increasing plant volume which may be a useful tool for growers that pack heads into clamshells – in some cases these are not sold by weight, but the head must reach an acceptable size to fill up the clam shell to be considered marketable. More experimentation should be done at a small scale before commercial producers adopt the water depth technique to make sure it is not detrimental to plant performance under their growing conditions.

This study aimed to discern whether water depth would have an affect on the yield of 'Rex' lettuce, and in the future, more research should be conducted on other cultivars and species of produce, such as kale, tomatoes, and hemp. For example, tomatoes grow well in rockwool slabs; however, this leads to a waste product, and the slab must be thrown out afterwards. Observing how tomatoes grow in a plastic channel given different water depths would be an interesting endeavor. Such a design may require some tweaks, such as drip irrigation at each plant, similar to methods used when growing in a rockwool slab and opposed to water flowing unidirectionally from one end of the channel to the other, as seen in an NFT system.

Further studies should also be carried out to continue looking into channel depth, as there are some interesting implications regarding the results, such as the notion of growing seedlings and young plants in an NFT system to intentionally grow larger roots before transplanting them into another system, such as a DWC floating raft system (or designing a system that can implement both methods, starting with NFT and switching to a deeper water column after a few weeks of growth) and observing possible effects of such a hybrid growing method. This question regards the potential nutrient uptake by plants as limited by the genetics of the plant. That is, would having more root mass lead to higher nutrient uptake?

Finally both a plant performance and economic analysis on the cost savings of being able to run a pump intermittently opposed to having to run the pump constantly would help shed light on other possible benefits of increasing the water column depth in plastic hydroponic channels.

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