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Crop physiological response to nutrient solution electrical conductivity and pH in an ebb-and-flow hydroponic system

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ABSTRACT

Small-scale hydroponic and aquaponic crop production is increasingly common in urban areas of the US and growers have questions about which system and crops to use. Hydroponic nutrient solution contains water soluble nutrients, electrical conductivity (EC) is maintained between 1 and 3 dS m^{-1}, and target pH is between 5.5 and 6. In contrast, plants in aquaponic systems are fertilized by aquaculture effluent, which is characterized by lower EC (less than 1 dS m^{-1}) and a target pH near 7.2. Duplicate greenhouse trials were conducted between 2013 and 2015 to assess the growth, yield, quality, and potential gross returns of four crops – basil (*Ocimum basilicum* L.), kale (*Brassica oleracea* L.), chipotle pepper (*Capsicum annuum* L.), and cherry tomato (*Solanum lycopersicum* L.) – grown in a recirculating ebb-and-flow system with nutrient solution EC and pH levels commonly observed in hydroponic (high EC–low pH) and small-scale aquaponic (low EC–high pH) systems. Solution pH and EC, plant height, and leaf greenness data were collected regularly throughout crop growth, and yield and percent soluble solids (°Brix) data were collected at harvest. Crops grown in the high EC–low pH solution approached a greater final height, but relative growth rate was not different from the low EC–high pH solution. Leaf chlorophyll content, estimated from leaf greenness, was up to 37% lower in the low EC–high pH solution. Marketable yield of basil and kale was reduced by 44% and 76% in the low EC–high pH solution, respectively. Yield loss in tomato and pepper was less severe (<32%), but still significant. Observed yield reductions were greater than previous comparisons of floating-raft aquaponic and hydroponic systems, which demonstrates the importance of root to nutrient solution contact area and fertigation frequency when using low EC–high pH nutrient solution (e.g., aquaculture effluent). Differences may also suggest there are components of aquaponic solution not tested in this mechanistic study (e.g., organic metabolites and alternative nutrient forms or ratios) that may contribute to crop growth and yield in aquaponics. On a per plant basis, kale ($10.62) and cherry tomato ($9.16) grown in the high EC–low pH solution provided the greatest potential gross returns, but farm-scale net profit potential will depend on many factors including plant spacing and input costs.

1. Introduction

Controlled environment agriculture, including hydroponic and aquaponic systems, has received renewed interest in the US due in part to the growth of urban agriculture. Urban food production has been proposed as one strategy for the redevelopment of vacant lots and buildings in depopulated cities, particularly in the north central US. Vacant lot food production is popular, but there are legitimate concerns about soil contamination and recontamination via atmospheric deposition of pollutants in urban areas (Wortman and Lovell, 2013). As a result, some advocates of urban agriculture argue that food production should occur primarily in controlled environments to limit exposure to contaminants and also to increase crop productivity towards greater food security. For example, Grewal and Grewal (2012) suggest that the city of Cleveland, Ohio could theoretically achieve up to 100% self-reliance in fruits and vegetables through the heavy use of rooftop hydroponic farming methods.

Despite the growing interest in hydroponic food production, there are concerns about the sustainability of hydroponic systems due to complete dependence on synthetically produced mineral nutrient solutions. More specifically, the production and use of synthetic fertilizers may contribute to greenhouse gas emissions (Hashida et al., 2014) and eutrophication of surface waters or strain municipal wastewater management facilities after disposal. One proposed solution to these problems is aquaponics—the integration

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of aquaculture and hydroponic plant production in a closed-loop system where synthetic fertilizers and water disposal are almost completely eliminated (Rakocy et al., 2006). In aquaponics, nutrients in fish effluent are filtered and used by plants in a recirculating closed-loop hydroponic system. Aquaponics may also improve the sustainability of aquaculture because nitrification and plant biofiltration of nutrients mitigates the buildup of compounds potentially toxic to fish (e.g., ammonia) and reduces the need for complete water exchange (Rakocy et al., 2006).

While aquaponic systems are perceived by many as the more sustainable production method, there are inherent differences in the chemistry of nutrient solutions between hydroponic and aquaponic systems. In aquaponics, concentrations of plant available nutrients in solution are driven by many factors including, fish species, growth stage, stocking density, feeding rate and feed composition, and rates of microbial nitrification (Rakocy et al., 2006; Tyson et al., 2004). Given the complexity of these interacting factors, the concentration of nutrients and chemical composition is understandably variable across aquaponic systems, though most research suggests the electrical conductivity (EC) in aquaponic solution is typically between 0.3 and 1.1 dS m^{-1} (Graber and Junge, 2009; Lennard and Leonard, 2006; Pantanella et al., 2012; Rakocy et al., 2006; Roosta and Hamidpour, 2011). The ideal nutrient strength in a hydroponic solution varies by hydroponic system, crop species, growth stage, and planting density, but is typically between 1 and 3 dS m^{-1} (Hashida et al., 2014; Rouphael and Colla, 2005; Sarooshi and Cresswell, 1994). Aquaponic solution is consistently deficient in potassium and iron, and these elements must be supplemented by adding to solution as potassium hydroxide and iron chelates, or via foliar application (Rakocy et al., 2006; Roosta and Hamidpour, 2011). These elements are deficient in aquaponic solution because they are not present in most commercial fish feed, but concentrations of other essential nutrients can be relatively low even when they are present in the feed. For example, recent analysis of solution from a former commercial aquaponic farm (Sweet Water Organics; Milwaukee, Wisconsin, USA) revealed low levels of nitrogen, phosphorus, potassium, and calcium, relative to nutrient levels in Hoagland's solution and other common hydroponic nutrient solutions (Table 1; Hoagland and Synder, 1933; Resh, 2012).

The other key chemical difference between aquaponic and hydroponic solutions is pH. Solution pH in aquaponic systems is a compromise between bacterial and plant demands. Bacterial transformation of ammonia to nitrite and further to nitrate is optimized at pH 8.5, but plant nutrient uptake for many crop species is optimized near pH 6.0; thus, pH in aquaponic systems is managed near pH 7.0 to ensure sufficient rates of nitrification without jeopardizing plant uptake potential of essential nutrients in solution (Tyson et al., 2004). Higher pH values in aquaponic solution may limit the uptake efficiency of certain essential elements, like iron, which is already limited in aquaponic solution (Alam, 1981; Rakocy et al., 2006). Additional key differences exist between the chemistry of aquaponic and hydroponic solutions (e.g., dissolved organic matter and organic metabolites in aquaponic solution; Rakocy et al., 2006), but nutrient strength (EC) and pH seem to have the strongest potential for influencing physiology and yield of plants.

Comparisons of yield and quality of vegetable crops in aquaponic versus hydroponic solution have been mixed. Pantanella et al. (2012) found that lettuce yields were not different between hydroponic solution (EC = 1.7 dS m^{-1} and pH 5.5) and a high stocking density aquaponic solution (EC = 0.6–1.0 dS m^{-1} and pH 6.5–7.0). However, lettuce yield was reduced by 18% in a low density aquaponic solution (EC = 0.4–0.5 dS m^{-1}) relative to hydroponics, demonstrating the importance of fish stocking density and feeding rate on nutrient availability to plants in aquaponics. While some studies have reported equal yields between aquaponic and hydroponic systems, the comparisons are often highly confounded (i.e., Graber and Junge, 2009) or lack an experimental control (i.e., Savidov et al., 2007). Roosta and Hamidpour (2011) observed reduced vegetative growth of tomato in an aquaponic system (EC = 0.54 and pH 7.7) relative to a hydroponic system (EC and pH not reported), but fruit yield was not different. Differences in crop quality may also exist between the two systems, but evidence is limited. Pantanella et al. (2012) observed reduced chlorophyll content in aquaponic relative to hydroponic lettuce at mid-maturity, but differences were not detectable at harvest. In contrast, Roosta and Hamidpour (2011) reported increased leaf greenness and chlorophyll content in aquaponics compared to hydroponics. Graber and Junge (2009) reported severe potassium deficiency in tomato fruit from aquaponic systems, but the deficiency was easily corrected with the addition of potassium hydroxide to raise solution pH.

Limited evidence on the topic suggests that vegetable crop growth, yield, and quality in hydroponic and aquaponic systems varies by species, cultivar, and the characteristics of a specific system (e.g., fish stocking density in aquaponics or pH in hydroponics), demonstrating a need for further research. Moreover, the specific effects of pH and EC differences between systems have not been studied in a mechanistic way. This information is essential for current and especially beginning growers (e.g., aspiring urban farmers) seeking advice about how to maximize profitability in a controlled environment production system. Rakocy et al. (2006) suggest that culinary herbs (i.e., basil) are up to 17 times more profitable than fruiting crops (i.e., okra) per unit area in a floating raft hydroponic system. However, questions remain about the yield, quality, and profit potential of culinary herbs, leafy crops, and fruiting crops in hydroponic compared to aquaponic conditions. The objective of this study was to assess the growth, yield, quality, and potential gross returns of four crops – basil (*Ocimum basilicum* L.), kale (*Brassica oleracea* L.), chipotle pepper (*Capsicum annuum* L.), and tomato (*Solanum lycopersicum* L.) – grown in a recirculating ebb-and-flow system with nutrient solution EC and pH levels commonly observed in hydroponic (high EC–low pH) and small-scale aquaponic (low EC–high pH) systems.

2. Materials and methods

2.1. Experimental design

Duplicate greenhouse trials were conducted in 2013/14 and 2014/15 at the University of Illinois at Urbana—Champaign Plant Care Facility (latitude 40.10°, longitude −88.22°; elev. = 230 m). Greenhouse temperatures in both trials were maintained between 25.6 and 27.9 °C during the day and between 19.0 and 22.5 °C at night. Plants were exposed to a 16 h day photoperiod and natural light was supplemented with 250 μE PAR m^{-2} s^{-1} artificial light when outdoor light intensity was less than 700 W m^{-2}. A factorial (2 × 4) randomized complete block design was used with four replicate blocks, two nutrient solution treatments, and four crops for a total of 32 experimental units. However, plant response data was analyzed within crop species. Each experimental unit consisted of four plants in 15 cm diameter, 1.4 L netted pots resting in a European leach tray (15 cm wide × 91 cm long × 10 cm deep).

2.2. Crop management

Plants were grown in a coco coir media and fertigated via the ebb and flow method four to six times per day for ten minutes at a time, depending on crop growth stage and estimates of evapotranspiration. Crop species included basil (*Ocimum basilicum* L. cv. Genovese), kale (*Brassica oleracea* L., dwarf blue curled vates type), chipotle pepper (*Capsicum annuum* L. cv. Cajun Belle), and cherry

Table 1
Chemical characteristics of nutrient solution from a former commercial aquaponic farm (Sweet Water Organics, Milwaukee, Wisconsin, USA), Hoagland's solution, the high EC–low pH (ideal hydroponic) and low EC–high pH (mimicked aquaponic) experimental treatments, and the well water used in the experiment.

	Sweet Water Organics[a]	Hoagland solution[b]	Experimental treatments[d]		
			High EC–low pH	LowEC–high pH	Well water
pH	7.36	[c]5.5–6.8	5.8	7.2	8.7
EC	0.84 $dS\,m^{-1}$	[c]1–3 $dS\,m^{-1}$	0.7–2.2 $dS\,m^{-1}$	0.5–1.0 $dS\,m^{-1}$	0.33 $dS\,m^{-1}$
		($mg\,L^{-1}$ (ppm))			
NO_3-N	58	210	176	44	1
PO_4-P	6	31	48	12	0.04
K	20	234	216	54	2
SO_4-S	26	64	42	10	0
Ca	81	200	235	29	13
Mg	45	48	31	7.8	15
B	0.08	0.1	0.5	0.13	0.4
Fe	–	–	3	0.75	0.01
Mn	–	–	0.5	0.13	0
Zn	–	–	0.15	0.04	0
Cu	–	–	0.15	0.04	0
Mo	–	–	0.1	0.03	0.01

[a] Duplicate samples analyzed from within hydroponic subsystems of the Sweet Water Organics recirculating, closed loop aquaponic system with tilapia and mixed lettuce varieties.
[b] Hoagland and Synder (1933).
[c] Range of solution pH and EC in typical hydroponic nutrient solutions (Resh, 2012).
[d] Nutrients added to well water with background nutrient concentrations described herein.

tomato (*Solanum lycopersicum* L. cv. Tiny Tim). Seeds of each crop were planted in a peat-based soilless mix (Sunshine Mix #1; Sun Gro Horticulture, Agawam, MA, USA) in seedling trays and transplanted into coco coir and netted pots when at least one true leaf was fully emerged.

After being transplanted into the ebb-and-flow, recirculating hydroponic systems, crops received only water (no nutrient solution) for two days to aid in root development and to avoid transplant shock. Thereafter, crops received one of two nutrient solution treatments: "high EC–low pH" or "low EC–high pH". The high EC–low pH solution, intended to mimic ideal hydroponic nutrient solution chemistry, was maintained at a target pH of 5.8 and included 974 $mg\,L^{-1}$ (recommended rate) of Peters Professional Hydroponic Special (1.1N–4.8P–21.6K; JR PETERS, Inc., Allentown, PA, USA) supplemented with 964 $mg\,L^{-1}$ of $Ca(NO_3)_2$. The low EC–high pH solution, intended to mimic solution EC and pH commonly observed in small-scale aquaponic systems, was maintained at a target pH of 7.2 and included 244 $mg\,L^{-1}$ of Peters Professional Hydroponic Special and 241 $mg\,L^{-1}$ of $Ca(NO_3)_2$ (Table 1). Well water was added to nutrient reservoirs every one to three days to replace water lost through evapotranspiration. Nutrient reservoirs were completely drained and replaced weekly with a fresh mix of the assigned nutrient solution to maintain target EC levels (2.1 or 0.9 $dS\,m^{-1}$) and minimize the potential for disease. Solution pH in each experimental unit was tested two times weekly and adjusted up as needed with potassium hydroxide or adjusted down as needed (more often the case due to alkalinity of well water; Table 1) with phosphoric acid or acetic acid.

Aquaponic systems are inherently complex with a number of possible confounding factors including fish species, stocking density, growth stage, and feeding rate, hydroponic subsystem (e.g., floating raft, NFT, or ebb-and-flow), water quality, and microbial populations and activity. This ecological complexity creates challenges for designing mechanistic research studies to compare aquaponic and hydroponic systems. In light of these challenges, water chemical conditions typical of a small-scale aquaponic system were mimicked by using a water-soluble hydroponic nutrient solution described above and in Table 1. While this approach does not capture the true essence of an aquaponic system, it does allow for the mechanistic isolation of the effects of nutrient solution pH and EC on vegetable crop physiology, which is the objective of this study. A similar "mimic" approach has been successfully used to isolate the effect of pH on nitrification rate in aquaponic systems (Tyson et al., 2004).

2.3. Data collection

Nutrient solution EC ($dS\,m^{-1}$) was sampled from each experimental unit with an EC/pH meter (HANNA Instruments; Woonsocket, RI, USA) immediately after mixing new nutrient solutions and immediately prior to emptying old nutrient solutions between 85 and 120 days after transplanting in trial 2. Solution EC was not recorded in trial 1. Crops were grown for 124 and 120 days after transplanting in trials 1 and 2, respectively, and plant height and leaf greenness were recorded at least once every two weeks. Plant height was measured from the base of the stem to top of the newest, fully-emerged leaf when extended vertically. Leaf greenness, a response well-correlated with leaf chlorophyll content, was measured near the middle of the newest fully emerged leaf with an atLEAF+ meter (FT Green, LLC; Wilmington, DE, USA; Zhu et al., 2012). Leaf chlorophyll content was estimated from atLEAF+ values using the following regression ($R^2 = 0.72$) from Zhu et al. (2012):

$$y = 52.4x + 28.1$$

where y is the atLEAF+ value and x is leaf chlorophyll content ($\mu g\,cm^{-2}$).

Approximately 25 and 50 days after transplanting, one of four plants was removed from each experimental unit for destructive sampling of biomass and leaf area. Removal of plants also served to increase spacing between remaining plants within an experimental unit to mitigate any confounding effects of shading. Crops were harvested as needed, as often as two times per week, depending on crop. Number and fresh mass of marketable and non-marketable leaves (kale), sprigs (basil), and fruit (tomato and pepper) were recorded at each harvest interval. Marketable yield was combined with available direct market price data (USDA–AMS, 2015) to estimate gross economic returns for each crop. Crop quality was measured at a single harvest interval in trial 2 using the °Brix test for total soluble solids. A subsample of the marketable crop portion (leaves or fruits) was pressed and total soluble solids (%) in the extracted juice was measured with an OPTi 38-02 digital refractometer (Bellingham + Stanley Ltd., Kent, UK).

2.4. Statistical analysis

Plant height over time was fit to a three-parameter logistic growth model commonly used for annual crops (Paine et al., 2012):

$$\text{Height} = \frac{A}{1 + \exp^{((x_0 - \log(\text{DAP}))/b)}}$$

where DAP is days after planting, A is a parameter representing the upper asymptote, x_0 is a parameter representing the inflection point of the curve, and b is a scale parameter (Pinheiro and Bates, 2000). Two models were fit: parameters varied by solution treatment in the first model and in the second model parameter values were assumed to be equal across treatments. These models were compared for each crop using an F-test to test the null hypothesis that all parameter values were equal across treatments (Ritz and Streibig, 2008). Non-linear analyses and F-tests were conducted in R (R Core Team, 2015).

All data were pooled across trials, but plant response data (e.g., height and yield) were analyzed within each crop. EC data were analyzed with a repeated measures analysis of variance using a generalized linear mixed model with nutrient solution, time, and their interaction as the fixed effects, and replicate block and trial as the random effects (Proc Mixed; SAS 9.3). Season average of leaf chlorophyll content, and marketable, nonmarketable, unripe, and total crop yield was analyzed as above, but without the use of repeated measures. Least square (LS) means and standard errors were calculated for all significant fixed effects and differences among treatments were determined using a rejection level of $\alpha = 0.05$.

3. Results

3.1. Solution chemistry and nutrient removal

Solution pH was maintained at an average of 5.78 ± 0.01 ($\pm$standard error) and 7.23 ± 0.01 across all crops in the high EC–low pH and low EC–high pH treatments, respectively. Nutrient inputs were four times greater in the high EC–low pH treatment compared to low EC–high pH treatment (Table 1), which led to corresponding differences in measured solution EC (Fig. 1). Nutrient removal, estimated from changes in EC between 85 and 120 days after transplanting, varied among crop species. In general, nutrient uptake was greatest in tomato and pepper and lowest in kale (Fig. 1).

3.2. Crop growth and leaf chlorophyll

Plant height over time varied between nutrient solutions for kale, pepper, and tomato, but not basil (Table 2 and Fig. 2). Differences between treatments were largely driven by differences in the upper asymptote of the growth curves (Table 2). Indeed, final plant height was significantly greater in the high EC–low pH solution for kale ($p = 0.002$) and trending in that direction for pepper ($p = 0.11$) and tomato ($p = 0.09$). Despite differences in the upper limit for plant height, relative growth rate was not different between treatments in any crop (data not shown).

Leaf chlorophyll content (μg cm^{-2}), estimated from atLEAF+ measures of leaf greenness, was greater in high EC–low pH solution for all crops (Fig. 3; $p < 0.01$). The difference was greatest in pepper where chlorophyll content was reduced by as much as 37% in the low EC–high pH solution.

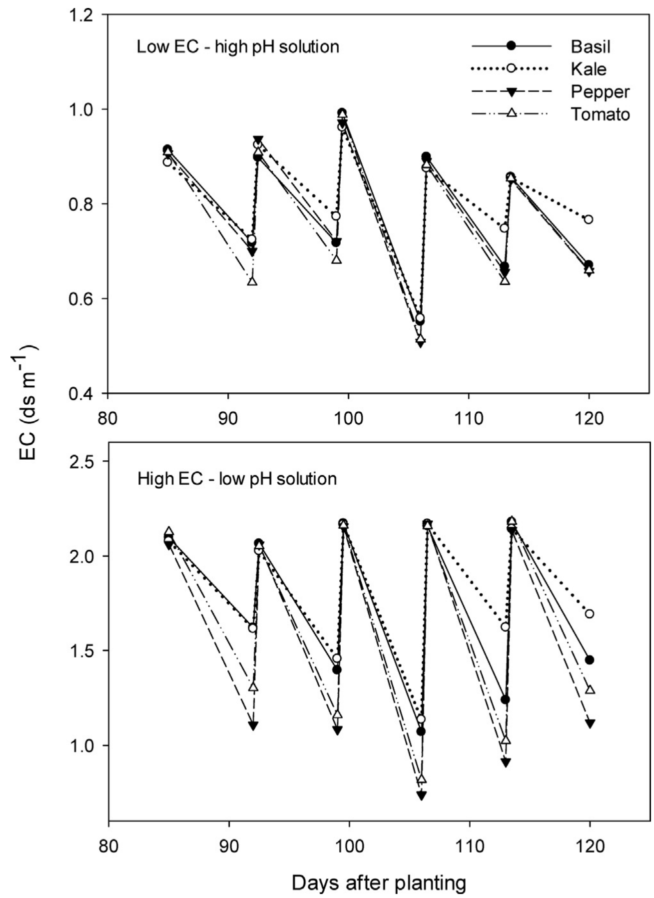

Fig. 1. Changes in electrical conductivity (dS m^{-1}) of low EC–high pH (mimicked aquaponic; top) and high EC–low pH (ideal hydroponic; bottom) solutions between 85 and 120 days after transplanting for basil, kale, pepper, and tomato in trial 2. Nutrient solutions were discarded and restocked one time per week to maintain target EC and pH levels.

Table 2
Parameter estimates for of low EC–high pH (mimicked aquaponic; top) and high EC–low pH (ideal hydroponic; bottom) solution treatments in each crop for a three-parameter logistic growth model where A represents the upper asymptote, x_0 represents the inflection point of the curve, and b is a scale parameter. "Standard errors of the parameter estimates are included in parentheses." p-values are included from the F-test to test the null hypothesis that parameter estimates between treatments within each crop are equal.

	Parameter estimates			
	A	x_0	b	p-value
Basil				0.056
Low EC–high pH	100.1 (20.4)	4.36 (0.23)	0.52 (0.10)	
High EC–low pH	89.5 (10.6)	4.17 (0.12)	0.45 (0.07)	
Kale				<0.001
Low EC–high pH	38.1 (2.8)	3.78 (0.07)	0.38 (0.09)	
High EC–low pH	50.5 (4.1)	3.90 (0.08)	0.42 (0.08)	
Pepper				0.007
Low EC–high pH	108.8 (7.2)	4.11 (0.05)	0.24 (0.04)	
High EC–low pH	119.3 (7.6)	4.07 (0.05)	0.26 (0.04)	
Tomato				<0.001
Low EC–high pH	65.1 (2.1)	3.81 (0.03)	0.24 (0.03)	
High EC–low pH	76.4 (3.3)	3.88 (0.04)	0.30 (0.04)	

3.3. Crop yield and quality

Marketable and total crop yields were generally reduced in the low EC–high pH solution (Table 3). Compared to the high EC–low pH solution, marketable and total basil yield were reduced by 44%

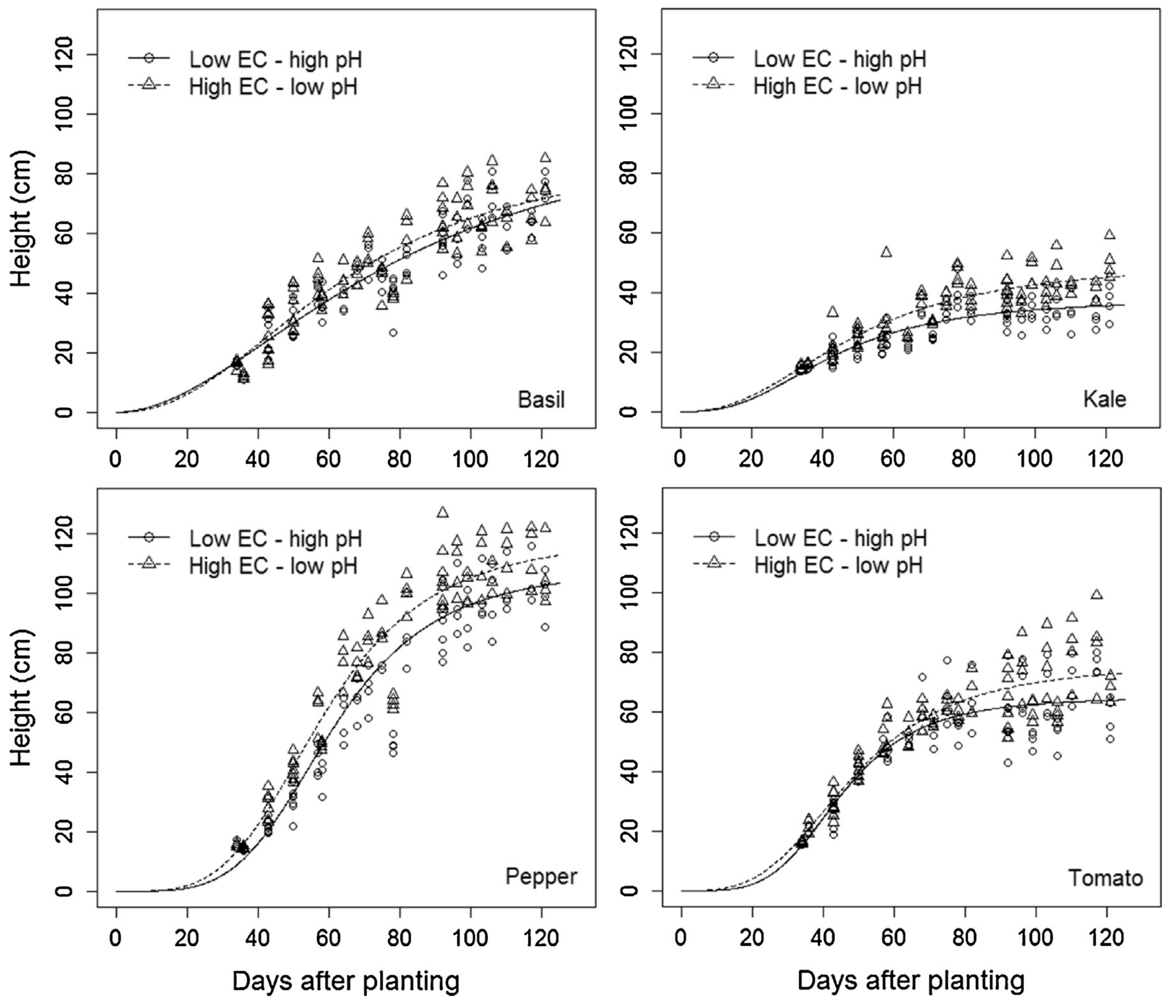

Fig. 2. Changes in plant height over time for basil, kale, pepper, and tomato grown in either low EC–high pH (mimicked aquaponic) or high EC–low pH (ideal hydroponic) solutions. Data were fit to predicted three-parameter logistic growth curves for low EC–high pH (solid line) and high EC–low pH (dashed line) solution treatments within each crop.

Table 3
Marketable, nonmarketable, unripe, and total yield (g plant^{-1}) of basil, kale, pepper, and tomato grown in either low EC–high pH (mimicked aquaponic) or high EC–low pH (ideal hydroponic) solutions. Potential gross revenue ($ plant^{-1}) from crop sales was calculated based on retail price data (USDA–AMS, 2015) and marketable yield of each crop. Standard errors within each crop are included below estimates of least squares means and an asterisk (*) indicates a significant treatment difference ($\alpha = 0.05$).

	Yield				
	Marketable (g plant^{-1})	Nonmarketable (g plant^{-1})	Unripe (g plant^{-1})	Total (g plant^{-1})	Gross revenue ($ plant^{-1})
Basil					
Low EC–high pH	187.8	46.9	–	234.7	2.48
High EC–low pH	338.1*	55.3	–	393.5*	4.47*
Std. Err.	92.7	43.4	–	50.9	1.23
Kale					
Low EC–high pH	195.6	216.6*	–	412.2	2.59
High EC–low pH	802.6*	23.9	–	826.5*	10.62*
Std. Err.	62.4	50.9	–	63.9	0.83
Pepper					
Low EC–high pH	113.6	9.7	149.1	272.4	1.50
High EC–low pH	140.5	32.6*	226.5*	399.6*	1.86
Std. Err.	50.4	6.0	186.6	140.1	0.67
Tomato					
Low EC–high pH	488.3	42.9	138.2	669.4	6.46
High EC–low pH	692.4*	56.0	256.3	1004.7	9.16*
Std. Err.	140.0	49.9	167.6	352.3	1.85

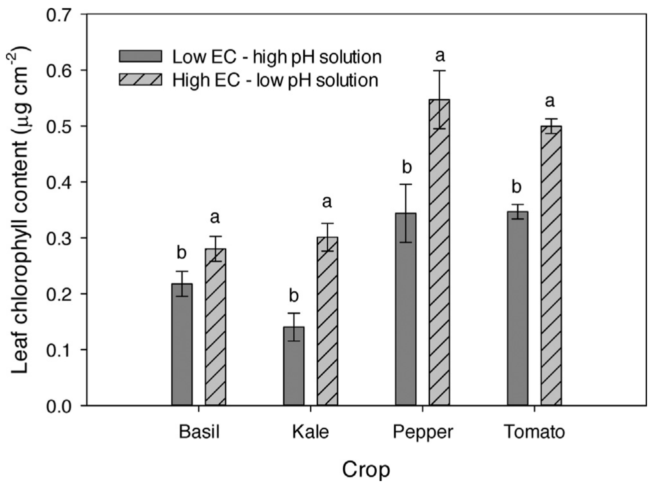

Fig. 3. Leaf chlorophyll content ($\mu g\,cm^{-2}$) of basil, kale, pepper, and tomato grown in either low EC–high pH (mimicked aquaponic) or high EC–low pH (ideal hydroponic) solutions estimated from atLEAF+ values collected on a weekly basis and averaged across both trials. Error bars represent ±one standard error of LS means and different letters above columns within a crop indicate a significant difference ($\alpha = 0.05$) between solution treatments.

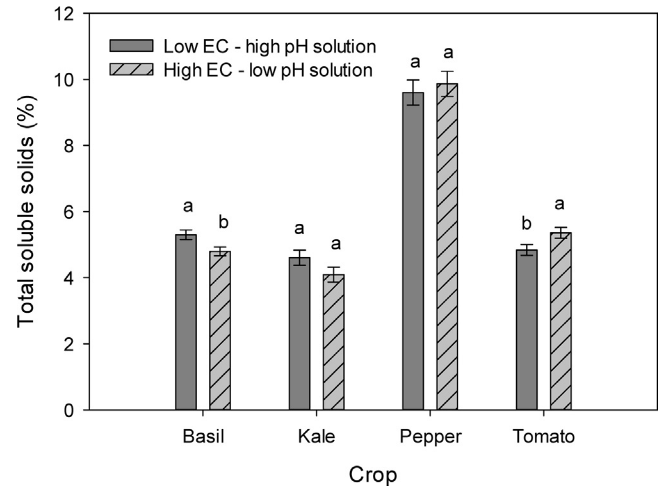

Fig. 4. Total soluble solids (%) of extracts from basil and kale leaves and pepper and tomato fruit at a single harvest in trial 2. Crops were grown in either low EC–high pH (mimicked aquaponic) or high EC–low pH (ideal hydroponic) solutions. Error bars represent ±one standard error of least squares means and different letters above columns within a crop indicate a significant difference ($\alpha = 0.05$) between solution treatments.

and 40% in the low EC–high pH solution, respectively ($p < 0.001$). Differences in kale yield were more pronounced: marketable and total yield were 76% and 50% lower in the low EC–high pH solution, respectively ($p < 0.001$). Moreover, chlorosis and yellowing of leaves increased the proportion of non-marketable kale leaves from the low EC–high pH solution ($p < 0.001$). Yield differences in pepper and tomato were not as consistent. Total yield of pepper was reduced by 32% in the low EC–high pH solution ($p = 0.006$), but marketable yield was not different between treatments ($p = 0.33$). Similarly, marketable tomato yield was reduced by 29% in the low EC–high pH solution ($p = 0.03$), but total yield was only trending higher in the high EC–low pH solution ($p = 0.08$).

Total soluble solids (%), estimated from refractometric Brix readings, were only different between solution treatments in basil ($p = 0.03$) and tomato ($p = 0.05$), but the direction of the response was not consistent. Percent soluble solids were 9% lower, but 11% greater in the high EC–low pH solution compared to the low EC–high pH solution for basil and tomato, respectively (Fig. 4).

3.4. Potential economic returns

Based on available retail price data (USDA–AMS, 2015) and assuming a direct-to-consumer marketing model (e.g., farmers' markets), kale grown in the high EC–low pH solution was the highest-returning crop on a per plant basis (Table 3). However, cherry tomato in the same solution was nearly as profitable as kale. Adjusting economic returns per plant for appropriate crop population densities suggests economic potential is similar among species within a given nutrient solution. If basil were to be planted in the high EC–low pH solution at a final density of 8 plants m^{-2} compared to 4 tomato plants m^{-2}, gross revenue potential would be essentially equal between the two crops (\$36 m^{-2}). Kale would likely be spaced at approximately 4 plants m^{-2}, which suggests a slightly greater gross return per unit area (\$42 m^{-2}).

4. Discussion

4.1. Solution chemistry and nutrient removal

The pH levels targeted in this experiment were consistent with those observed in previous comparisons of hydroponic and aquaponic solutions (e.g., Pantanella et al., 2012; Roosta and Hamidpour, 2011). Ideal pH in hydroponic systems ranges from 5.5 to 6.0, but aquaponic solution pH is managed between 7.0 and 7.5 in an effort to balance the physiological demands of fish, plants, and nitrifying bacteria (Tyson et al., 2004). Differences in solution pH will alter plant nutrient uptake; specifically, uptake of iron and other metals will be reduced at higher pH levels commonly observed in aquaponic solution (Alam, 1981).

Abundant nutrient uptake and removal is an essential crop characteristic in aquaponic systems, often just as important as crop yield and profitability, because a primary function of plants in the system is solution biofiltration (Graber and Junge, 2009; Rakocy et al., 2006). Results of this study suggest tomato and pepper were the most effective for nutrient removal and may be appropriate crop choices for aquaponic systems, even if yield or profit potential is lower than leafy green crops (Fig. 1). This result is consistent with previous studies where nutrient removal by tomato was greater than pak choi (Hu et al., 2015), cucumber, and eggplant in aquaponic systems (Graber and Junge, 2009).

4.2. Crop growth and leaf chlorophyll

A primary benefit of controlled environment agriculture is increased crop growth rate and reduced time to maturity (Adams et al., 2001). The lack of differences in relative growth rates between solution treatments suggests that this benefit was not jeopardized in the low EC–high pH solution (mimicked aquaponic solution) despite decreased final plant height. Differences in plant height observed here are consistent with Roosta and Hamidpour (2011) who reported a 25% reduction in height for tomato grown in aquaponic compared to hydroponic solution. They also observed 102% greater leaf biomass and 69% greater shoot biomass in hydroponic compared to aquaponic solution. However, root mass was 48% greater in aquaponics compared to hydroponics (Roosta and Hamidpour, 2011). Increased root:shoot ratio in aquaponics is consistent with plant physiological response to low nutrient soil environments (Wortman and Dawson, 2015).

Reduced leaf greenness was likely the result of reduced nitrogen in the low EC–high pH solution (Table 1; Fallovo et al., 2009). Leaf greenness and chlorophyll content are positively correlated with photosynthesis and yield (Buttery and Buzzell, 1977; Waskom et al., 1996); thus, crops in aquaponic solution may have reduced photosynthetic and yield potential. Moreover, leaf greenness influences the marketability of leafy vegetable crops and herbs (Wang et al., 2005). Chlorosis of kale and basil leaves, which was not uncommon in the low EC–high pH solution, may reduce or eliminate the fresh market potential for these crops.

4.3. Crop yield and quality

Yield loss of leafy greens grown in the low EC–high pH solution is consistent with the results of Pantanella et al. (2012) who reported an 18% reduction of lettuce yield in low-density aquaponic (EC = 0.4–0.5 dS m^{-1}) compared to hydroponic solution. However, yield differences were not observed between a high-density aquaponic (EC = 0.6–1.0 dS m^{-1}; more characteristic of the water chemical conditions in this study) and hydroponic solution (Pantanella et al., 2012). Although yield loss was less severe in fruiting compared to leafy crops, these results are in contrast to recent studies demonstrating similar fruiting crop yields between hydroponic and aquaponic systems. Roosta and Hamidpour (2011) reported no difference in tomato yield between aquaponic and hydroponic solutions, despite increased leaf and shoot biomass and plant height in hydroponic solution. Graber and Junge (2009) reported similar yields of tomato, eggplant, and cucumber between hydroponic and aquaponic systems, despite nutrient concentrations three to ten times lower in the aquaponic solution. Strong yield loss observed in the low EC–high pH solution of this study (up to 76%) compared to the lack of yield differences observed in aquaculture effluent solutions from previous studies suggests there may be other solution characteristics driving plant productivity in aquaponic systems.

Solution pH and nutrient concentrations (EC) were isolated for comparison in this mechanistic study, but other key differences exist between aquaponic and hydroponic solutions. Aquaponic solution contains relatively high amounts of dissolved organic matter and organic metabolites that may contribute to nutrient availability, uptake, and crop yield (Rakocy et al., 2006). Similarly, nutrient forms and ratios (e.g., NO_3^- and NH_4^+) may be different between systems. Another possible explanation for the magnitude of yield loss observed in this study is that nutrient concentrations (e.g., EC) decreased over a one week period until being restocked to target levels (Fig. 1). In a typical aquaponic system, nutrient concentrations are stable or increase slightly over time. Despite this difference, EC in the mimicked aquaponic solution was rarely lower than 0.6 dS m^{-1}, which is within the range of solution ECs reported in previous studies on aquaponics (e.g., Pantanella et al., 2012).

The most likely explanation for the magnitude of yield loss observed in this study is related to the type of hydroponic sub-system used and the frequency of fertigation. Most hydroponic sub-systems studied in aquaponics are floating raft systems (e.g., Pantanella et al., 2012; Rakocy et al., 2006; Roosta and Hamidpour, 2011), but the hydroponic system used in this study was an ebb-and-flow system with coco coir media. An ebb-and-flow hydroponic sub-system is logistically compatible with aquaponics and not uncommon, but floating raft systems are more typical (Tyson et al., 2011). Results from Lennard and Leonard (2006) suggest that yield and nutrient removal rate in aquaponic systems are positively correlated with root to water contact area. In a floating raft system the root surface area is almost entirely immersed in nutrient solution at all times, but roots of crops in the ebb-and-flow system of this study were flooded up to six times and immersed in solution for only 40–60 min per day. The coco coir media retains moisture and water and nutrient uptake undoubtedly occurs between flooding events, but the root to solution contact area is likely much lower during the “ebb” phase in this system. Intermittent irrigation and reduced root contact area with solution may have contributed to reduced nutrient uptake and yield in the low EC–high pH treatment of this study, relative to reports for aquaponic yields in floating raft systems already in the literature.

The ebb-and-flow system and other soilless media hydroponic systems are designed to prevent water stress to the plant, but nutrient deficiency can develop if nutrient solution concentrations are low. Schon and Compton (1997) found that *Cucumis sativus* L. became nitrogen deficient when fertigated intermittently in rockwool media at low nitrogen concentrations (90–175 mg L^{-1}), but the plant was sufficient at high nitrogen concentrations (225–275 mg L^{-1}). Thus, intermittent fertigation to meet crop evapotranspiration demand does not seem compatible with the low nutrient concentrations commonly observed in small-scale aquaponic systems. Further research is needed to determine if increasing the frequency or duration of fertigation events in soilless media systems could help to mitigate nutrient deficiency in low EC–high pH aquaponic solutions. In the absence of this research, it seems the floating raft hydroponic sub-system is most suitable for aquaponic plant production.

Differences in crop quality between treatments were significant, but rather small (less than 0.6% soluble solids) and unlikely to have biological or practical significance. Soluble solids (°Brix) in sweet pepper cultivars, for example, can range from 6 to 11% and differences of less than 0.5% are unlikely to influence perceptions of quality or taste (Eggink et al., 2012). Despite yield loss in the low EC–high pH solution, results suggest that some aspects of crop quality may not be adversely affected in aquaponic solution.

4.4. Potential economic returns

Not surprisingly, reduced yield in the low EC–high pH solution resulted in proportional decreases in potential gross returns. However, after adjusting for plant spacing, all crops appear equally profitable in the high EC–low pH solution. In addition to yield and crop spacing, growers should also consider time to harvest maturity. Rakocy et al. (2006) suggested that culinary herbs (e.g., basil) are profitable crops in aquaponic systems in part because of the short culture period compared to fruiting crops. This suggestion is supported by results from pepper in this study, where the majority of fruit was harvested unripe 120 days after transplanting because it failed to reach maturity by the conclusion of the experiment. Contrast that with basil and kale where harvest began as early as 50 days after transplanting and continued for the duration of the study.

Overall, it is important to note the economic consequences of yield loss in the low EC–high pH solution (Table 3). If culinary herbs and vegetables have a significantly greater profit potential than fish, as suggested by Rakocy et al. (2006), then growers should seriously consider whether any potential loss in yield, quality, or marketability of crops grown in aquaponic solution can be justified. Where yield loss is most severe in aquaponic solution (e.g., kale), it may be wise to consider a hydroponic solution or alternative management of the aquaponic solution to mitigate nutrient deficiency. However, results of this study combined with previous research (Graber and Junge, 2009; Roosta and Hamidpour, 2011) suggest that fruiting crops (e.g., tomato and pepper) may be less susceptible to yield and economic loss in aquaponic systems.

5. Conclusions

Crop growth rate was not different between nutrient solutions, but crops fertilized with the high EC–low pH solution had greater leaf greenness and approached a greater final height than crops fertilized with the low EC–high pH solution. These physiological changes contributed to significant reductions in yield and economic returns – up to 76% – for crops fertilized with the low EC–high pH solution characteristic of small-scale aquaponic systems. A portion of this yield loss may be attributed to reduced root to solution contact area in the tested ebb-and-flow hydroponic system, but yield loss in aquaponics has also been reported in floating raft hydroponic sub-systems (Pantanella et al., 2012). These findings demonstrate the importance of maintaining an intensive, high-density aquaculture sub-system in aquaponics (with proportionately high feeding rates) to support sufficient nutrient levels. However, the intensity of aquaculture management required for successful aquaponic production described by Rakocy et al. (2006) is rarely duplicated. Instead, many start-up aquaponic farms are "plant-centric" and maintain a low-density aquaculture sub-system that requires less intensive management. Unfortunately, the result is often nutrient deficiency, physiological disorder (e.g., chlorosis), and reduced marketable yield, as observed in this study. Aquaponic systems were designed to be "fish-centric" with vegetable crops as a secondary commodity added to the system as a sustainable option for biofiltration of aquaculture effluent (Rakocy et al., 2006). However, the greater profit potential of herbs and vegetables, relative to fish, draws many "plant-centric" farmers into the system without the technical expertise required to manage the aquaculture sub-system intensively enough to realize the profit potential described by Rakocy et al. (2006). Despite published examples of profitable aquaponic vegetable and herb production (e.g., Graber and Junge, 2009; Rakocy et al., 2006; Tokunaga et al., 2015), results of this study highlight the potential for yield loss associated with a low EC–high pH solution in a recirculating ebb-and-flow hydroponic sub-system. Thus, growers should carefully consider the economic feasibility of small-scale aquaponics compared to hydroponics before investing in these new systems for urban and local food production (Tokunaga et al., 2015).

Yield loss in aquaponics associated with low nutrient availability and uptake may be at least partially managed through the use of plant growth promoting rhizobacteria (Mangmang et al., 2015) and foliar applications of fertilizer (Roosta and Hamidpour, 2011). Alternatively, aquaponic growers may consider the possibility of supplementing aquaponic solution with synthetic nutrients or "charging" media with organic nutrients. Commercial aquaponic growers commonly supplement solution with potassium and iron to prevent known deficiencies in fish feed (Rakocy et al., 2006); thus, small-scale aquaponic growers might consider taking this strategy a step further and supplementing with a complete nutrient solution to limit deficiencies of other essential nutrients like nitrogen. This strategy could still reduce fertilizer costs and environmental impacts relative to growing in pure hydroponic solution without sacrificing yield or quality of plants in the aquaponic system. However, further research would be needed to determine the effects of nutrient supplementation on fish biology and productivity. If a grower wanted to avoid the use of synthetic nutrients (e.g., "natural" or potentially certified organic systems), another possibility is to "charge" or supplement soilless media with an organic fertility source (e.g., compost or meals). This strategy would only be feasible in soilless media systems, not floating raft systems, but may be helpful in preventing the nutrient deficiency and reduced yield observed in this study and others. However, further research is needed to determine the effect of solid organic fertilizers on solution chemistry and crop growth in hydroponic and aquaponic systems.

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