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Historical, Current, and Future Perspectives for Controlled Environment Hydroponic Food Crop Production in the United States

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***Abstract*. Controlled environment (CE) food crop production has existed in the United States for many years, but recent improvements in technology and increasing production warranted a closer examination of the industry. Therefore, our objectives were to characterize historical trends in CE production, understand the current state of the U.S. hydroponics industry, and use historical and current trends to inform future perspectives. In the 1800s, CE food production emerged and increased in popularity until 1929. After 1929, when adjusted for inflation (AFI), CE food production stagnated and decreased until 1988. From 1988 to 2014, the wholesale value of CE food production increased from $64.2 million to $796.7 million AFI. With the recent increase in demand for locally grown food spurring an increase in CE production, both growers and researchers have been interested in using hydroponic CE technologies to improve production and quality. Therefore, we surveyed U.S. hydroponic food crop producers to identify current hydroponic production technology adoption and potential areas for research needs. Producers cited a wide range of technology utilization; more than half employed solely hydroponic production techniques, 56% monitored light intensity, and more than 80% monitored air temperature and nutrient solution pH and electrical conductivity. Additionally, the growing environments varied from greenhouses (64%), indoors in multilayer (31%) or single-layer (7%) facilities, to hoop houses or high tunnels (29%). Overall, producers reported managing the growing environment to improve crop flavor and the development of production strategies as the most beneficial research areas, with 90% stating their customers would pay more for crops with increased flavor. Lastly, taking historical data and current practices into account, perspectives on future hydroponic CE production are discussed. These include the importance of research on multiple environmental parameters instead of single parameters in isolation and the emphasis on not only increasing productivity but improving crop quality including flavor, sensory attributes, and postharvest longevity.**

CE food crop production has fluctuated in productivity and evolved in technology over history. For example, early U.S. CE food production generally took place in glasshouses heated by "hot beds" of manure (Dalrymple, 1973), whereas currently food is produced not only in glasshouses but plastic-glazed houses and indoor facilities heated through many methods, most of which are not manure-based. By examining both historical trends and current practices, we can deduce possible future CE hydroponic production trends. Therefore, our goals were to 1) characterize the historical trends in CE production, 2) conduct a national survey with the objectives of identifying current CE hydroponic production technology adoption and the research needs and priorities of the U.S. hydroponics industry, and 3) use historical trends and current practices to inform future perspectives.

Historical Perspectives of U.S. CE and Hydroponic Production

Although CE vegetable production has been reported to have originated during the Roman Empire, it was not until the early 1800s that commercial CE food production emerged in the United States. By 1900, an estimated 1000 facilities were growing 40 ha of winter vegetables in CE with ≈67% of crops grown in greenhouses and ≈33% grown in hotbeds and coldframes (Dalrymple, 1973; Galloway, 1900; Jensen and Collins, 1985). At this time, wholesale and retail annual CE vegetable sales were estimated to be $2.3 and $4.5 million, respectively (Dalrymple, 1973; Galloway, 1900). By 1929, the first year the U.S. Department of Commerce [USDC; these data are now collected by the U.S. Department of Agriculture (USDA)] Census of Horticultural Specialties reported vegetables grown under protected culture, 520 ha of vegetables were produced with 43%, 33%, 18%, and 6% of the crop value consisting of tomato (*Solanum lycopersicum*), cucumber (*Cucumis sativus*), lettuce (*Lactuca sativa*), and other crops, respectively, and sales totaling $10.0 million [$136.9 million adjusted for inflation to 2014 (AFI); USDC – Bureau of the Census, 1930; Table 1]. Although food was grown under protected culture in glass-glazed greenhouses, hydroponic production was limited (Jensen and Collins, 1985).

Hydroponic production can generally be defined as growing plants without mineral soil, using "an inert medium such as gravel, sand, peat, vermiculite, pumice, perlite, coco coir, sawdust, rice hulls, or other substrates" instead and adding the nutrients necessary for growth (Resh, 2013). Although this definition includes soilless substrate growing systems typical to potted floriculture production, by convention, hydroponic production excludes this growing method (Gomez et al., 2019). A more common description used by the USDA Census of Horticultural Specialties and this study, defines hydroponic production as food crops grown "in nutrient solutions without soil" (USDA – National Agriculture Statistics Service, 2015).

Interest in hydroponic production arose from issues with fertilization and soil as a substrate (Dalrymple, 1973). This led to the development of sand culture (Shive and Robbins, 1937), water culture (Gericke, 1933), and then subirrigation (Withrow and Biebel, 1937) hydroponic production systems in the late 1920s and 1930s. Commercial production-scale hydroponics in the United States began during World War II when the U.S. military used hydroponics to produce fresh food on Pacific islands during the war (Jensen and Collins, 1985), and by 1972, commercial hydroponic production greenhouses emerged across the United States (Dalrymple, 1973).

From 1929, protected vegetable cultivation stagnated or decreased until 1988, after which CE food production again increased in popularity. For example, in 1929, food crops worth $136.9 million AFI were produced under 5.2 million m^2 (USDC – Bureau of the Census, 1930). By 1988, only $64.2 million AFI worth of vegetables grown under 1.2 million m^2 remained, a 53% AFI decrease in sales and a 77% reduction in production area (USDC – Economics and Statistics Administration, 1991; Table 1). The stagnation and decrease in CE food production was due to many factors, possibly including increased trade with Mexico; refrigeration and interstate infrastructure, making long-distance perishable food shipment feasible; and also the burgeoning floriculture industry, the value of which increased from $82 million in 1929 ($555 million AFI to 1988) to just under $2 billion in 1988 (USDC – Bureau of the Census, 1930; USDC – Economics and Statistics Administration, 1991). However, CE vegetable production has been increasing since 1988, and by 2014, $796.7 million worth of vegetables was produced in 8.7 million m^2 of protected environments (USDA – National Agriculture Statistics Service, 2000, 2015).

A seemingly large increase in greenhouse food production took place between 1988 and 1998, during which the number of operations nearly doubled from 581 to 1015 producers, and sales grew from $64.2 million AFI to $322.2 million AFI (402% AFI increase in total value; USDC – Economics and Statistics Administration, 1991; USDA – National Agriculture Statistics Service, 2000). However, an even greater increase in the number of greenhouses producing food occurred between 1998 and 2014, when the number of operations increased by 148% (1506 additional operations) and sales increased from $322.2 million AFI to $797.7 million (148% AFI increase). Over those 16 years, large increases in cucumber ($60.0 million AFI increase, 339%), fresh cut herbs ($26.1 million AFI increase, 158%), lettuce ($42.0 million AFI increase, 311%), strawberry (*Fragaria* ×*ananassa*; $847,000 AFI increase, 1193%), and tomato ($230.5 million AFI increase, 135%) sales occurred, while pepper (*Capsicum annum*) remained relatively steady ($13.7 million AFI decrease, 19%; USDA – National Agriculture Statistics Service, 2000, 2015; Table 1).

When comparing 1929 to 2014, both Census of Horticultural Specialties reports cited cucumber, lettuce, and tomato as the most commonly produced CE crops. Additionally, the 2014 report also cited fresh cut culinary herbs, pepper, and strawberry as top CE crops (USDC – Bureau of the Census, 1930; USDA – National Agriculture Statistics Service, 2015; Table 1).

The portion of protected culture crops grown hydroponically was first reported in 2009, with 73% of CE vegetable crops produced in protected culture grown hydroponically. Tomato was the highest value food crop grown in CE, with sales totaling $355 million AFI, and 89% of those fruits were produced hydroponically (USDA – National Agriculture Statistics Service, 2010; Table 1). Similarly, 92% of the cucumber crop produced in CE was grown hydroponically, while only 4% and 3% of pepper and strawberry crops, respectively, grown in CE were produced hydroponically in 2009 (USDA – National Agriculture Statistics Service, 2010). In 2014, the top hydroponically produced CE crops were as follows: cucumber (30.0 million kg), fresh cut herbs (3.4 million kg), lettuce (7.0 million kg), and tomato (75.1 million kg) with 91%, 21%, 70%, and 86% of cucumber, fresh cut herbs, lettuce, and tomato crops, respectively, grown in protected culture produced hydroponically (USDA – National Agriculture Statistics Service, 2015).

Although peer-reviewed aquaponics industry surveys (Love et al., 2014, 2015; Villarroel et al., 2016) and vegetable industry surveys, including a "State of the Vegetable Industry Survey" administered by *American Vegetable Grower* magazine (Gordon, 2016), have been conducted, these reports have focused primarily on aquaponics or outdoor production. A "State of Indoor Farming" survey was conducted by Agrilyst, a climate control system company, in 2017 reporting data on facility type, crops produced, yield, profitability, technology, and growers' future plans (Agrilyst, 2017). However, this survey did not identify specific production practices and technology adoption, nor did it identify the U.S. CE hydroponic industry's research needs. This information is valuable for firms entering CE production or considering it for a near-term opportunity, in addition to educational programming efforts to inform future entrepreneurs. Therefore, a more comprehensive survey focusing on specific production practices and research priorities was needed to focus CE research and extension efforts on topics most beneficial to current and future producers.

Current U.S. Hydroponic Crop Production Practices: A Survey

Approach. To achieve our objectives, we developed a 23-question online survey for the hydroponics industry (https://osf.io/rvtem/?view_only=ff2affcc7eb442118c12cc4cf08bd78e). The questions were designed to gather information pertaining to 1) demographics and business operations, 2) young plant propagation; 3) hydroponic food production (transplant to harvest), and 4) research priorities. The survey consisted of four open-ended, 16 closed-ended multiple choice, and two constant sum questions. Additionally, we asked respondents to rate several topics relating to hydroponic production on a 4-point Likert scale in terms of their perceived benefit to their operation. The scale ranged from 1 (not at all beneficial) to 4 (very beneficial). Means and standard deviations were calculated from the responses.

With the survey content and methods approved by the Michigan State University committee on research involving human subjects (IRB x17-241e), the survey was created on the SurveyMonkey (San Mateo, CA) online platform to improve ease of access to survey participants. Requests to advertise the survey and recruit participants were sent to several widely read industry trade publications focused on greenhouse and CE crop production, including *Growertalks*, *Greenhouse Product News*, *Greenhouse Grower*, *HortAmericas*, *HortiDaily*, *Inside Grower*, *Produce Grower*, and *Urban Ag News*. Each publicized the survey by providing a link to it through their websites, e-newsletters, and blogs (Kuack, 2017). Research topic benefit was analyzed using Tukey's honestly significant difference test with JMP (version 12.0.1; SAS Institute Inc., Cary, NC). Descriptive statistics were used to represent and compare all other data.

Results and Discussion

Producers and production area. From the first advertisement (4 Apr. 2017) to the closing date (21 June 2017), we obtained 42 useful responses from 19 states. Fifty-three percent of the respondents produced hydroponic food crops solely, and an additional 30% produced food in-ground and hydroponically. Whereas 10% reported producing hydroponic food crops as well as floriculture crops, 5% were switching from floriculture to hydroponic food production. One firm reported growing hydroponically for breeding and research. Although more than half of respondents only used hydroponic production techniques, 45% grew hydroponically in addition to floriculture or in-ground food production. Increasing diversification potentially increases economic benefits including social capital formation, greater profitability, improved labor management, and improved economic resiliency (Boody et al., 2005; Mishra et al., 2004). Many respondents appear to be food-centric in production, which helps extension programming target specific, focused groups of producers in meetings and the trade press.

The distribution of area dedicated to hydroponic production for the responding firms was wide (Fig. 1). Only one firm reported a hydroponic production area of less than 46 m^2, and 19% of the firms reported hydroponic area in production of 9290 m^2 or more. Hydroponic area in production for the most frequently reported category was 93 to 464 m^2, and the mean and median area were 2629 m^2 and 697 m^2, respectively. Firms produced crops in greenhouses (64%), indoors in multilayer (31%) or single-layer (7%) facilities, and hoop houses or high tunnels (29%; data not shown).

Indoor production, used by 38% of the growers surveyed, creates opportunity for

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Table 1. The number of operations, area under protection, kilograms produced, total sales, and sales adjusted for inflation of food crops grown under protection in the United States between 1929 and 2014 as reported by the U.S. Department of Commerce or the U.S. Department of Agriculture. Values do not include mushroom production.

Crop	Yr	No. of operations	Area under protection (m^2)	Kilograms produced		Sales ($)	Sales adjusted for inflation ($)[z]
				Total	Hydroponic		
Cucumber	1929[y]	682	1,281,480	—[x]	—	3,247,951[w]	44,429,690
	1949[v]	126	—	—	—	1,277,176[u]	12,447,996
	1959[v]	71	104,415	—	—	477,766[u]	3,853,694
	1970[v]	66	85,579	—	—	515,881[u]	3,192,403
	1979[t]	153	194,725	—	—	3,426,000[w]	11,733,000
	1988[s]	133	264,402	—	—	8,912,000[w]	18,018,000
	1998[r]	201	280,381	—	—	12,226,000[w]	17,697,000
	2009[q]	343	558,440	12,034,713	11,040,710	—[p]	—
	2014[q]	733	1,021,655	32,940,105	30,028,586	77,650,000[w]	77,650,000
Herbs, fresh cut	1998	192	438,967	—	—	30,995,000	44,865,000
	2009	323	550,822	—	—	—	—
	2014	524	1,287,079	16,112,055	3,457,599	70,929,000	70,929,000
Lettuce	1929	1,141	1,434,866	—	—	1,832,505	25,067,382
	1949	330	—	—	—	1,393,021	13,577,079
	1959	293	936,543	—	—	2,455,882	19,809,314
	1970	233	1,035,689	—	—	3,061,278	18,943,966
	1979	193	479,844	—	—	4,557,000	15,607,000
	1988	100	160,536	—	—	4,047,000	8,182,000
	1998	129	108,604	—	—	9,330,000	13,505,000
	2009	338	255,762	—	—	53,823,000	59,628,000
	2014	763	402,270	9,947,417	7,002,196	55,547,000	55,547,000
Pepper	1988	78	26,477	—	—	500,000	1,011,000
	1998	165	140,005	—	—	5,277,000	7,368,000
	2009	265	114,271	826,536	28,848	2,191,000	2,427,000
	2014	534	327,205	3,493,523	—	5,996,000	5,996,000
Strawberry	1998	26	3,437	—	—	49,000	71,000
	2009	76	87,236	177,173	5,942	525,000	582,000
	2014	130	57,879	320,009	—	918,000	918,000
Tomato	1929	1,384	1,958,458	—	—	4,130,451	56,501,671
	1949	711	—	—	—	10,077,398	98,219,360
	1959	770	2,637,788	—	—	16,152,412	130,286,469
	1970	688	1,999,083	—	—	14,034,821	86,851,037
	1979	734	1,211,270	—	—	17,447,000	59,753,000
	1988	414	599,318	—	—	13,282,000	26,853,000
	1998	715	1,608,245	—	—	117,856,000	170,597,000
	2009	1,148	3,712,591	145,475,102	129,071,160	320,454,000	355,017,000
	2014	1,889	3,957,391	87,330,003	75,111,721	401,133,000	401,133,000
Other	1929	883	527,314	—	—	796,080	10,889,816
	1949	125	—	—	—	298,865	2,912,888
	1959	81	144,410	—	—	459,583	3,707,028
	1970	98	107,160	—	—	746,785	4,621,295
	1979	128	80,547	—	—	1,254,000	4,295,000
	1988	118	148,645	—	—	5,001,000	10,111,000
	1998	193	360,185	—	—	46,891,000	67,875,000
	2009	345	1,339,941	49,604,952	11,911,971	101,350,000	112,281,000
	2014	851	1,614,654	86,600,944	33,375,916	184,491,000	184,491,000
Total	1929	—	5,202,118	—	—	10,006,987	136,888,560
	1949	768	2,546,185	—	—	13,046,460	127,157,322
	1959	—	3,823,156	—	—	19,545,643	157,656,504
	1970	—	3,227,511	—	—	18,358,765	113,608,700
	1979	866	1,966,386	—	—	26,684,000	91,388,000
	1988	581	1,199,471	—	—	31,743,000	64,176,000
	1998	1,015	2,939,824	—	—	222,624,000	322,248,000
	2009	1,476	6,619,063	227,835,320	165,649,393	553,270,000	612,943,000
	2014	2,521	8,668,132	236,744,055	150,190,920	796,664,000	796,664,000

This table does not include data from the Census of Agriculture in years when the Census of Horticultural specialties was not conducted because, although protected culture food production was reported, the reports include mushroom cultivation. Therefore, the numbers cannot be directly compared with the numbers reported in this table because mushrooms were excluded (USDC – Bureau of the Census, 1930, 1952, 1962, 1982; USDC – Social and Economics Statistics Administration, 1973; USDC – Economics and Statistics Administration, 1991; USDA – National Agriculture Statistics Service, 2000, 2010, 2015).

[z] Values adjusted for inflation to 2014 using the consumer price index (U.S. Department of Labor – Bureau of Labor Statistics, 2019).

[y] Vegetables grown under glass, in coldframes, or other structures.

[x] Data not available.

[w] Total sales by operations, not just wholesale.

[v] Vegetables grown under glass.

[u] Value based on wholesale prices.

[t] Vegetables grown under protection.

[s] Greenhouse-produced vegetables.

[r] Greenhouse-produced food crops.

[q] Food crops grown under protection.

[p] Withheld to avoid disclosing data for individual operations.

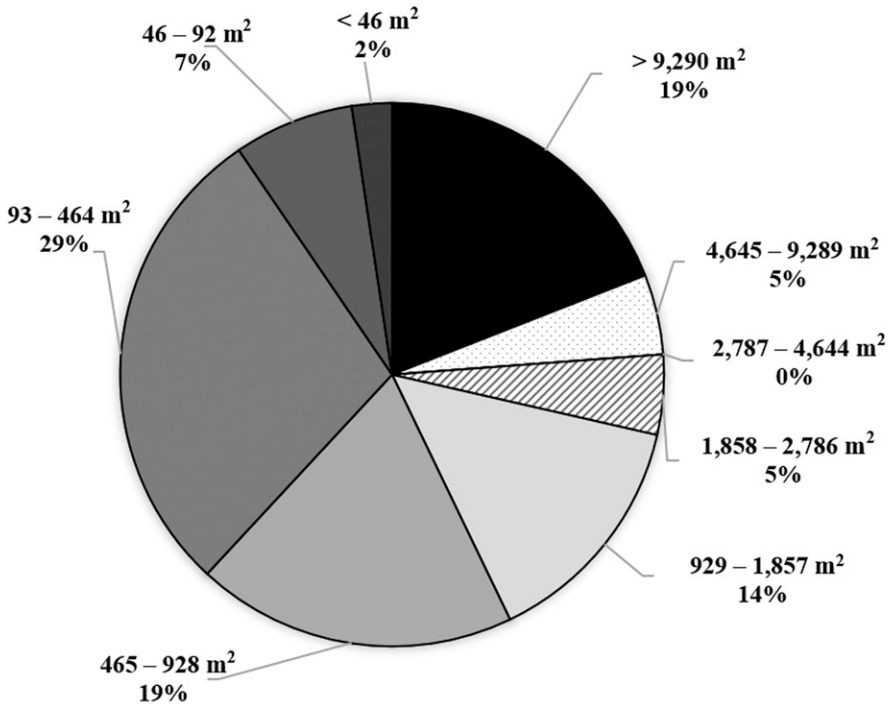

Fig. 1. The area of production dedicated to hydroponics per producer as reported by respondents to a 2017 hydroponic grower survey in the United States (n = 42).

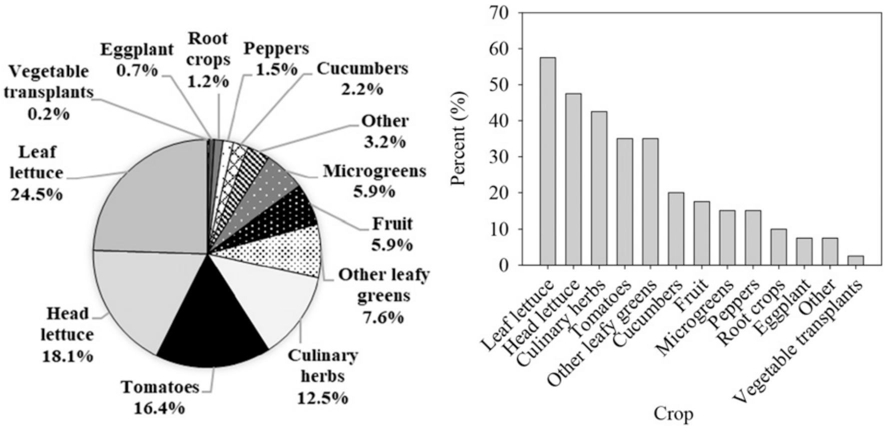

Fig. 2. The proportion of crops grown based on number of producers growing the crop weighted by the percent value of that crop compared with total (left), and the percentage of producers growing each crop (right), based on respondents of a 2017 U.S. hydroponic grower survey (n = 42).

increasing environmental control compared with traditional greenhouse production (used by 64% of respondents; data not shown). For example, greenhouses primarily rely on variable solar radiation for the majority or all of the photosynthetically active radiation used by plants, while light (photoperiod, spectrum, and quantity) provided to plants indoors is more precisely controlled. Additionally, temperature in a greenhouse is affected by solar radiation, nighttime long-wave radiation loss, and reduced insulation compared with indoor production, resulting in greater external environmental influences on temperature compared with indoor production. Finally, humidity (or vapor pressure deficit) can be readily increased in both indoor production and greenhouses. Reducing humidity in the two environments requires different strategies depending on outdoor humidity and temperature, energy costs, supplemental carbon dioxide (CO_2) use, and the willingness to introduce outside pests to indoor facilities (Gomez et al., 2019). However, the greater ability to control the growing environment in indoor compared with greenhouse production results in higher capital investment and operating costs.

Crops and production systems. Leaf lettuce (e.g., green leaf, red leaf) was produced by 58% of the respondents (Fig. 2). Head lettuce (e.g., boston/bibb/buttercrunch, and cos/romaine) was produced by nearly half of the firms, and fresh cut culinary herbs [e.g., basil (*Ocimum* spp.), cilantro (*Coriandrum sativum*), parsley (*Petroselinum crispum*), dill (*Anethum graveolens*), mint (*Mentha* spp.), rosemary (*Rosmarinus officinalis*), sage (*Salvia officinalis*), and thyme (*Thymus vulgaris*), etc.] were produced by 43% of respondents. Fourteen percent of firms produced microgreens, whereas other leafy greens [e.g., kale (*Brassica oleracea*), swiss chard (*Beta vulgaris* subsp. *vulgaris*), and spinach (*Spinacia oleracea*)] were grown by a third of the respondents. Five firms reported exclusive production of one of those categories of leafy greens (culinary herbs, head lettuce, leaf lettuce, or microgreens). Combined, leafy greens production accounted for 69% of the production based on the number of producers growing the crop weighted by the percentage of production (Fig. 2).

In 2014, the USDA Census of Horticultural Specialties only differentiated between the total weight of produce grown under protection and the weight of produce grown hydroponically. Data regarding the number of operations, area in production, and sales of hydroponically produced crops was not available. However, comparisons in trends can be made. Mirroring the 2014 USDA Census of Horticultural Specialties report stating more producers grow lettuce (763 producers) than fresh cut culinary herbs (524 producers) in CE, leaf and head lettuce were the most common hydroponically produced crops by survey respondents, followed by culinary herbs. However, the value of fresh cut culinary herbs produced in CEs in the United States ($70.9 million) was greater than lettuce ($55.5 million; USDA – National Agriculture Statistics Service, 2015; Table 1). The USDA reported tomato as the most commonly produced CE crop based on number of producers, weight, and value; however, only one-third of survey respondents reported producing tomatoes. Similarly, only 19% of the respondents produced cucumbers, whereas the USDA reported a similar number of operations producing cucumbers as lettuce (USDA, 2015; Table 1, Fig. 2). Fewer operations grew eggplant (*Solanum melongena*; 7%), fruit [e.g., strawberries, blueberries (*Vaccinium* spp.), and melon (*Cucumis* and *Citrullus* spp.), etc.; 17%], pepper (14%), and root crops [e.g., beets (*Beta vulgaris*), radishes (*Raphanus sativus*), and carrots (*Daucus carota* subsp. *sativus*), etc.; 10%]. Understanding crop diversity is critical for the improvement of extension materials and prioritization of research. Knowing that many firms do not have monocultures underscores the need to identify species-specific environment responses and cultural conditions to classify and group crops, thereby simplifying production and improving production efficiencies.

Nutrient-film technique (NFT) was the most frequently used hydroponic system (48% of respondents, 36% of production area), followed by dutch or bato bucket (33% of respondents, 18% of production area), then raft or deep-flow technique (DFT; 25% of respondents, 14% of production area; Fig. 3). The hydroponic production

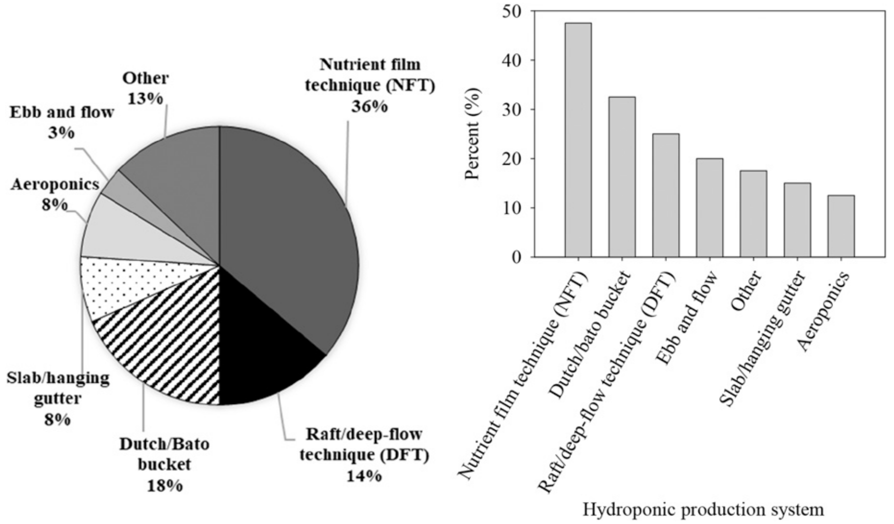

Fig. 3. The proportion of hydroponic production systems used by respondents of a 2017 U.S. hydroponic grower survey, based on space dedicated to each system (left), and the percentage of respondents using each type of production system based on frequency (right) (n = 42).

Table 2. The types of nutrient solution filters used by respondents of a 2017 U.S. hydroponic grower survey.

Filter type	No.
In-line	4
Unspecified	3
Bio	2
Mesh	2
Soil sock	2
Ultraviolet	2
Cloth	1
Diatomaceous earth	1
Paper	1
Particulate	1
Sand	1
Total respondents (n)	17^z

^{z}Some respondents used multiple filter types.

system used largely depends on the crop being produced. For example, dutch or bato bucket and slab or hanging gutter systems are more commonly used to produce strawberries and high-wire crops such as cucumbers, eggplant, peppers, and tomatoes, whereas NFT, raft or DFT, aeroponics, and ebb-and-flow systems are more commonly used for leafy greens including lettuce, culinary herbs, and microgreens (Jensen, 1997; Peet and Wells, 2005; Fig. 3).

Nutrient and water management. Municipal water was used by 62% of the firms, whereas well water was used by 29% of respondents. Fewer firms used reverse-osmosis or deionized (14%), reclaimed (19%), or other water sources (19%), including plasma-activated, spring, fish hatchery, gray, rain, and surface or pond water (data not shown). For young plant production, water was applied as overhead irrigation (50%), daily single-event subirrigation (39%), constant subirrigation (29%), or other (18%) including drip, fog, hand (type not specified), and multiple-event-per-day subirrigation (data not shown). In recirculating systems, only 43% reported filtering the nutrient solution, using in-line filters (10%), bio filter, mesh filter, soil sock, ultraviolet, (5% each), or other methods (13%; Table 2).

Water source is a key component of hydroponic culture. Because water used for plant production can vary widely in pH, alkalinity, electrical conductivity (EC), concentrations and ratios of specific nutrients, other chemical species, and the potential for pathogen contamination, understanding differences in water quality between sources is essential. For example, Argo et al. (1997) analyzed 4306 water samples from greenhouse producers across the United States and found the pH ranged from 2.7 to 11.3, EC varied from <0.01 to 9.8 dS·m^{-1}, and alkalinity from $CaCO_3$ ranged from 0 to 1120 mg·L^{-1}. When comparing hydroponic producer responses to a 2013 survey of ornamental plant growers, a higher percentage of ornamental producers (55%) used well water, whereas municipal water was used by a lower proportion of producers (27%; Hodges et al., 2015). Even though municipalities charge for water consumption, the majority of producers in our survey used municipal water. This may be due to the quality standards municipal water is held to by the U.S. Environmental Protection Agency (2009), which sets standards for more than 90 contaminants. As a result, water from municipalities is often more consistent in quality than well or surface water because it is tested and is safe for both human consumption and food crops, including hydroponic, production (Shaw et al., 2015). Additionally, the tendency of CEA facilities to be located in or near urban areas where municipal water is readily available could contribute to this trend. Although only used by 14% of producers surveyed, reverse-osmosis or deionized water is one method of ensuring consistent water quality with low nutrient contamination; however, the cost of these systems may be prohibitive. Reclaimed water (used by 19% of respondents) may reduce the amount of municipal or groundwater needed to produce a crop, but like surface water, it may be susceptible to both nutrient and pathogen contamination (Hanning et al., 2009; Runia, 1993). Due to the wide variation in quality and nutrients already present in the water (Argo et al., 1997) and the potential for pathogen contamination (Hanning et al., 2009), understanding water source inputs gives growers, extension personnel, and researchers a helpful starting point for managing nutrients.

Nutrient solution management is integral to successful hydroponic production. While the EC is a measurement of a solution's conductivity reflecting the total amount of fertilizer ions, pH of the nutrient solution and the relative proportion and concentration of these ions determines the availability and uptake of specific nutrients by the plant. Both EC and pH can be measured with commonly used sensors (as reported by 85% of respondents; Fig. 4) while more difficult to measure parameters, including specific nutrients and dissolved oxygen, were measured by only 54% and 28% of respondents, respectively. Additionally, 60% of respondents reported using sensors and/or automatic pumps to manage or monitor nutrient solution EC and temperature, whereas 57% and 21% used sensors and/or automatic pumps to manage and monitor pH and dissolved oxygen, respectively.

Researchers have reported different trends in plant growth and development, nutrient uptake, and quality in response to EC. For example, as EC increased from 1.4 to 3.0 dS·m^{-1}, lettuce fresh weight decreased when pH was adjusted daily, EC was not adjusted, and solutions were replaced every 2 weeks in a DFT system (Samarakoon et al., 2006). In contrast, as EC increased from 0 to 4.8 dS·m^{-1}, fresh weight of pakchoi (*Brassica campestris* L. ssp. *chinensis*) increased; however, plants were only irrigated three times per week, and the hydroponic production system type is unknown (Ding et al., 2018). Additionally, high-wire tomatoes grown with ECs ranging from 2.5 to 5.0 dS·m^{-1} irrigated daily and NFT-grown culinary herbs with ECs from 0.5 to 4.0 dS·m^{-1} and daily pH and EC adjustment had similar fresh weight among EC treatments (Currey et al., 2019; Walters and Currey, 2018; Wu and Kubota, 2008). The authors hypothesize that EC may not limit growth when adjusted continuously but may become a limiting factor when nutrient solutions are adjusted periodically in recirculating systems. A more consistent trend is observed between crops regarding nutrient uptake. For example, as EC increased, N concentration increased in pakchoi (Ding et al., 2018) and culinary herbs (Currey et al., 2019; Walters and Currey, 2018) and lycopene, fructose, glucose, and total soluble solids increased in tomato (Wu and Kubota, 2008).

Respondents who used recirculating systems varied in their practices for adjusting nutrient solution EC: 43% added specific

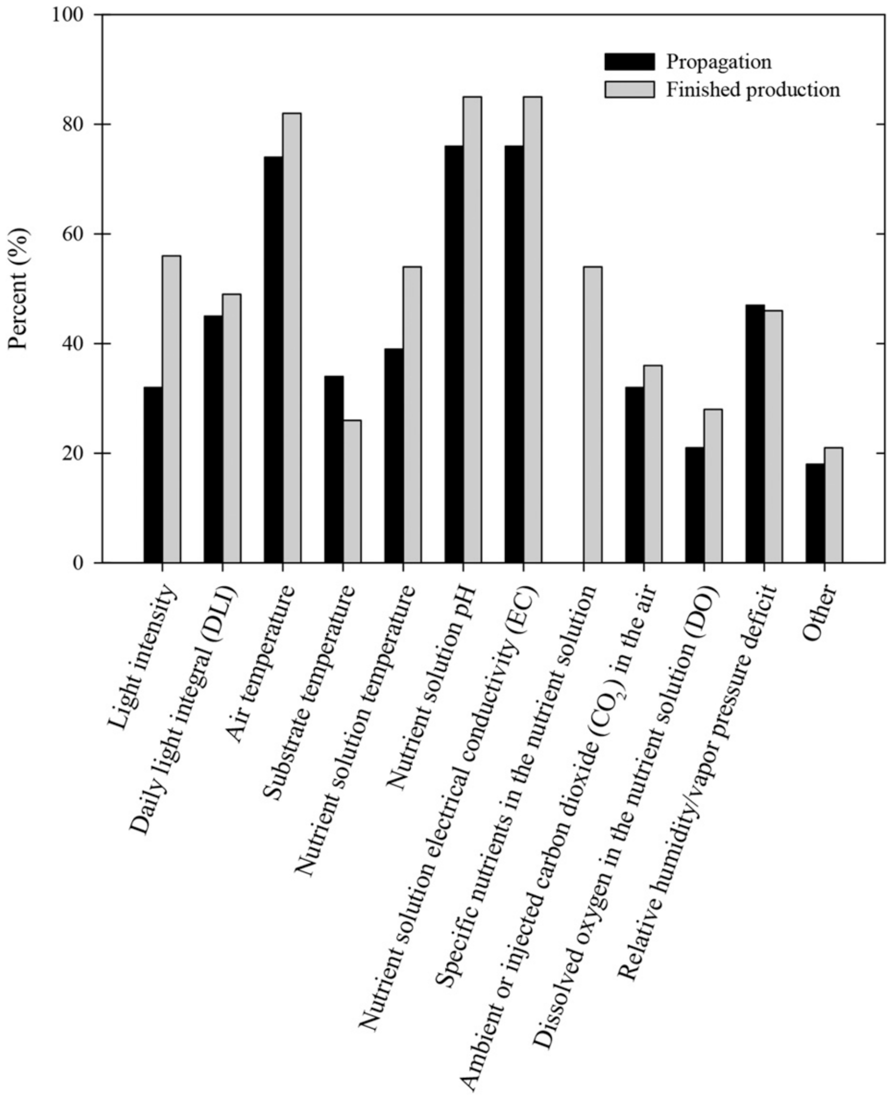

Fig. 4. The environmental and cultural parameters monitored by hydroponic growers in the United States during propagation (n = 38) and finished production (n = 39) based on responses to a 2017 survey of hydroponic growers in the United States.

nutrients; 38% added a complete, balanced prepackaged mix; 8% did not adjust EC; and 12% took other management steps including mixing their own fertilizer and adding water (data not shown). Growers most commonly replaced nutrient solutions completely every 1 to 3 months (28%), whereas 20% never completely replaced it; the remainder replaced the solution at differing intervals varying from every day to every 3 to 6 months (Fig. 5). The wide variation in methods to account for nutrient depletion and solution replacement aligns with the producers reporting research on nutrient solution formulations (mean = 3.1 ± 1.0) and nutrient solution pH (2.8 ± 1.0) being slightly to very beneficial (Fig. 6). Additionally, with the majority of producers surveyed monitoring and automatically adjusting nutrient concentrations, specific recommendations to aid growers in using automation to manage nutrients is needed. Research on crop-specific recommendations for specific mineral nutrient concentrations and ratios to maintain a balanced nutrient solution could improve crop quality, reduce excessive nutrient accumulation, reduce nutrient deficiencies, and conserve water and labor.

Growing environment: Monitoring and control. The number of environmental parameters monitored during propagation was less than those monitored during finished production. For example, 32% and 45% of producers surveyed monitored light intensity and daily light integral (DLI) during propagation, respectively, while 56% and 49%, respectively, monitored these parameters during finished production (Fig. 4). The use of supplemental lighting was more common during propagation (54%) than during finished production (45%), while the use of sole-source lighting was similar between propagation and finished production (21% and 20%, respectively; Fig. 7).

Even though supplemental lighting was more common during propagation than during finished production (Fig. 7), light intensity and DLI were monitored by more producers during finished production (Fig. 4). Using supplemental lighting to augment low sunlight intensities during propagation can increase yields. For example, McCall (1992) stated that increasing the supplemental photosynthetic photon flux density (*PPFD*) provided to tomatoes from 30 to 90 $\mu mol \cdot m^{-2} \cdot s^{-1}$ during transplant production not only increased plant height, leaf number, leaf area, and dry mass, but also yields for the first 16 weeks of production. Walters and Lopez (2018) reported increasing the sole-source light intensity provided to basil seedlings during the first two weeks of growth from 100 to 600 $\mu mol \cdot m^{-2} \cdot s^{-1}$ *PPFD* resulted in an 80% increase in fresh cut yield after transplanting and finishing plants in a common greenhouse environment. During finished production, light intensity is a key driver of yield. For example, as DLI increased from 2 to 20 $mol \cdot m^{-2} \cdot d^{-1}$, basil, cilantro, dill, oregano (*Origanum vulgare*), thyme, parsley, mint, and sage fresh weight increased by 8.1 g (thyme) to 175.1 g (dill) (Litvin, 2019). Crop quality including postharvest life, appearance, and flavor is also influenced by light intensity. For example, cucumber postharvest shelf life was prolonged, and the fruit color was a more desirable deep green when light intensities during production were higher (Lin and Jolliffe, 1996), and basil favor compounds increased as the DLI increased from 5 to 25 $mol \cdot m^{-2} \cdot d^{-1}$ (Chang et al., 2008).

By monitoring light intensity and DLI, producers can decide whether ambient light intensities are adequate or if supplemental lighting is necessary to improve production. Producers reported research on light quality (mean = 3.2 ± 1.0) and DLI (mean = 3.1 ± 1.1) as being moderately to very beneficial (Fig. 6). Light quality is particularly important to the 20% of respondents who used sole-source lighting, as 100% of the light is provided by electrical lighting compared with supplemental lighting, where a larger proportion of light is provided by the sun (Poel and Runkle, 2017). Light quality can influence crop quality; in tomato, red light increases while far-red light decreases carotenoid accumulation (Alba et al., 2000). Additionally, increasing blue light increases the plant quality of a variety of crops, including increasing lycopene and β-carotene in tomato fruits (Gautier et al., 2004) and increasing the concentration of flavor compounds basil, dill, and parsley (Ichimura et al., 2009; Litvin et al., 2020).

Given choices of air, substrate, and nutrient solution temperature, respondents indicated that air temperature was the most commonly monitored environmental parameter; 74% of producers measured air temperature during propagation and 82% measured it during finished production (Fig. 4). The rate of plant development is primarily driven by temperature (Heins et al., 1998). Because temperature can be a readily controlled environmental factor with a large impact on growth, development, and plant quality, it is commonly manipulated by growers. Target

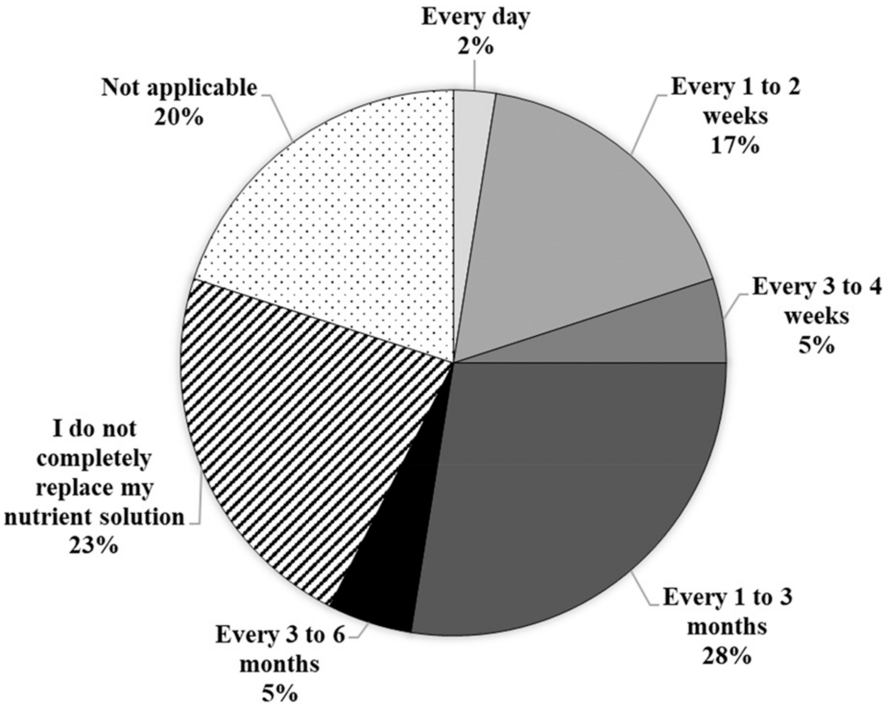

Fig. 5. The frequency of nutrient solution replacement as reported by respondents of a 2017 U.S. hydroponic grower survey (n = 40).

temperatures for crop production depend on many factors including the cardinal temperatures for different crop species, interactions with other environmental parameters, target finishing or harvest dates, desired size and quality, crop production stage, cost of cooling and heating, the ability to control the environment, time of year, and growing location. Models quantifying air temperature effects on cucumber (Slack and Hand, 1983), culinary herbs (Chang et al., 2005; Currey et al., 2016; Walters and Currey, 2019), lettuce (Scaife, 1973; Seginer et al., 1991), pepper (Nilwik, 1981), and tomato (Adams et al., 2001) have been published. In general, researchers have found that as temperature increases above the base temperature of a crop, the growth rate increases linearly until a species-dependent optimum temperature, above which the growth rate decreases. Some researchers have also investigated the interaction of temperature, light intensity, and plant age determining the optimal temperature may also be dependent on those factors (Nilwik, 1981; Pearce et al., 1993). However, more robust models including more data points across a broader temperature range and the interaction of temperature and other environmental parameters including light intensity, photoperiod, and CO_2 concentration, as well as cultural parameters including nutrient concentration and proportions, are needed. Additionally, temperature extremes can reduce fruit-set of flowering food crops and should be taken into consideration (Erickson and Markhart, 2002). Given commercial producers' ability to monitor temperature and the availability of research models on which to base growing decisions, the producers surveyed identified research on temperature as the fourth-lowest research priority, being moderately beneficial (mean = 3.0 ± 0.8; Fig. 6). However, production recipes, including the interaction of temperature and other environmental parameters, are deemed the second-highest research priority (mean = 3.3 ± 1.1; Fig. 6).

Thirty-six percent of producers surveyed monitored CO_2 concentration during finished production, whereas 32% monitored CO_2 during propagation. One-third of respondents injected CO_2 to reach target concentrations ranging from 350 to more than 1500 ppm (Table 3). During propagation and finished production, the same number of producers reported monitoring relative humidity or vapor pressure deficit (46% to 47%; Fig. 4).

Increasing CO_2 concentration to species-specific saturation points increases yield of cucumber (Wittwer and Robb, 1964), lettuce (Knecht and O'Leary, 1983; Wittwer and Robb, 1964), pepper (Fierro et al., 1994), strawberry (Wang and Bunce, 2004), and tomato (Morgan, 1971; Wittwer and Robb, 1964). However, only 36% of growers monitored CO_2 during finished production. CO_2 management was deemed the lowest research benefit as growers ranked it as slightly to moderately beneficial (mean = 2.7 ± 1.1; Figs. 4 and 6).

Crop quality. When asked if their customers would pay more for crops with increased flavor, 90% of respondents responded affirmatively, whereas 10% reported only their wholesale customers would pay more if the crop had improved nutrition or color (data not shown). Managing the growing environment to improve crop flavor was cited as the most beneficial research area (mean = 3.4 ± 0.7; Fig. 6). Many environmental and cultural factors can influence the flavor of crops including light intensity (Chang et al., 2008), light quality (Alba et al., 2000; Gautier et al., 2004; Litvin et al., 2020; Weisshaar and Jenkins, 1998), air temperature (Chang et al., 2005), CO_2 concentration (Wang and Bunce, 2004), and nutrition (Benard et al., 2009). However, increases in secondary metabolites do not necessarily result in improved flavor. For example, in a sensory panel, consumers deemed the flavor of basil grown at 23 °C under 400 or 600 $\mu mol \cdot m^{-2} \cdot s^{-1}$ *PPFD* too intense, whereas plants grown under 100 $\mu mol \cdot m^{-2} \cdot s^{-1}$ *PPFD* were not flavorful enough; however, plants grown under 200 $\mu mol \cdot m^{-2} \cdot s^{-1}$ *PPFD* had preferred characteristics (Walters et al., 2019). Similarly, increasing secondary metabolite production in brassicas can lead to increased health-promoting glucosinolates, but with the side effect of a bitter taste (Bell et al., 2018). With producers indicating their consumers would pay more for increased flavor, continued research to determine which type and intensity of flavor is preferred and by which consumer segments is essential to improving crop quality to increase prices.

Research priorities. Given the range of production systems, cultural practices, and environmental conditions affecting hydroponic food crop production, coupled with the lack of science-based production recommendations, additional research is warranted. However, research priorities should reflect the needs of the commercial industry. The most important research priorities, on a scale of 1 to 4, as reported by growers were manipulating the growing environment to improve crop flavor (mean = 3.4 ± 0.7), production recipes (e.g., lighting, CO_2, temperature, nutrients) (mean = 3.3 ± 1.1), light quality [e.g., supplying different wavelengths of light using light-emitting diodes (LEDs)] (mean = 3.2 ± 1.0), food safety guidelines (mean = 3.2 ± 0.9), postharvest recommendations (3.1 ± 0.9), and energy-use and resource-use management (mean = 3.1 ± 1.0). The topic with the lowest mean score was CO_2 management (mean = 2.3 ± 1.1; Fig. 6). These priorities, based on their perceived benefit to growers, should be taken into consideration when determining research priorities for hydroponic food crop production.

Future Perspectives and Conclusions

Although CE hydroponic production has been used to grow food crops for many years, the recent increase in CE food production is creating need for additional research to increase production efficiencies and profitability, improve yields and produce quality, and address production challenges. Through this producer survey, we are establishing baseline data on the variability in production type, technology adoption, and research needs of hydroponic food crop producers. Educators, extension specialists, and researchers can use these data to better understand the current state of the U.S. hydroponics industry, identify gaps

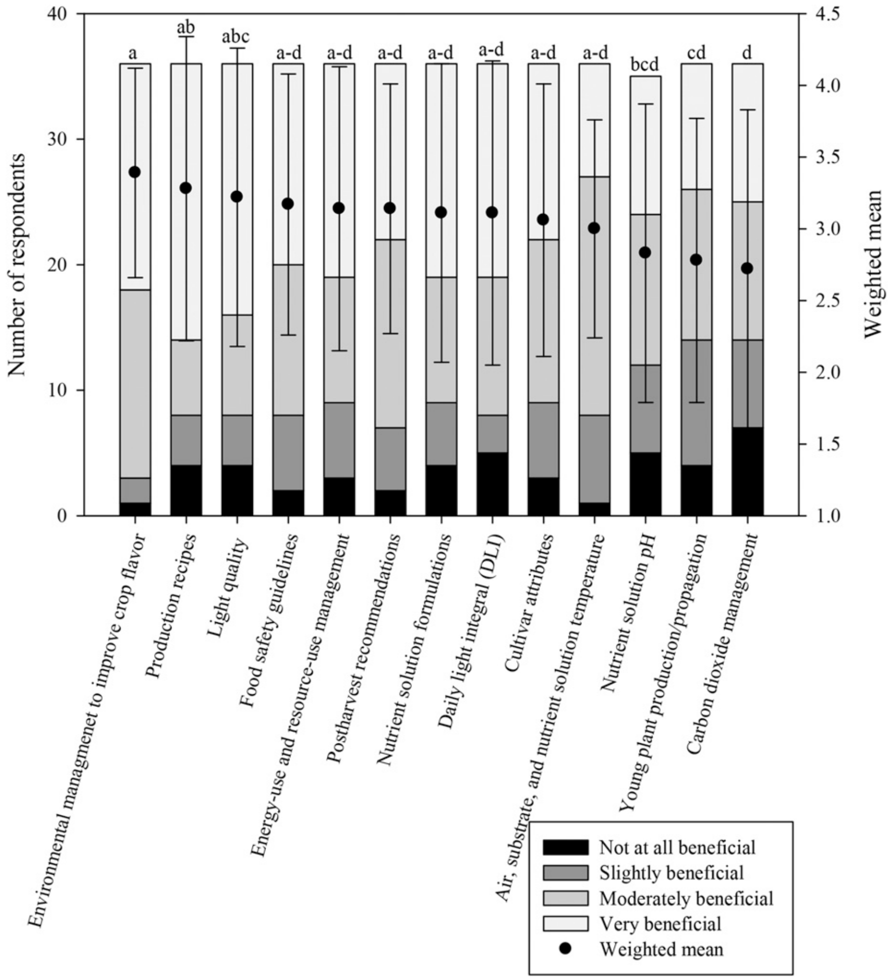

Fig. 6. The degree of benefit of research topics as reported by respondents to a 2017 survey of U.S. hydroponic growers. Means ± SD were calculated by assigning values to the responses, 1 = not at all beneficial, 2 = slightly beneficial, 3 = moderately beneficial, 4 = very beneficial. Research topics that share letters do not differ by Tukey's honestly significant difference test at $P \leq 0.05$ (n = 36).

Table 3. The target carbon dioxide (CO_2) concentration as reported by respondents to a 2017 survey of hydroponic growers in the United States.

CO_2 concn (ppm)	No.
>350	1
400–1200	1
500	1
700	1
700–1000	1
800	1
1000	2
1100	1
1200	2
>1500	1
Unknown	2
Total respondents (n)	14

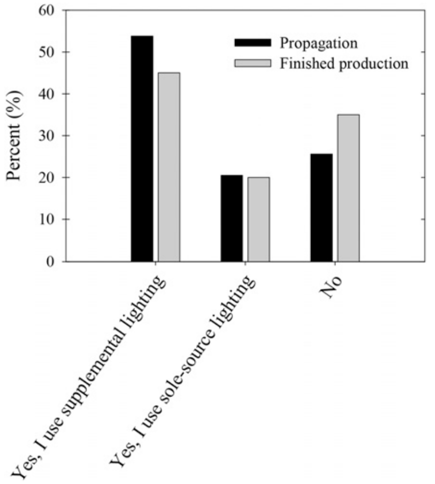

Fig. 7. The use of supplemental or sole-source lighting based on responses to a 2017 survey of hydroponic growers in the United States (n = 40).

in both knowledge and technology adoption, provide extension resources or research to aid in filling those gaps, and educate future industry members on current practices.

On the basis of the survey results and the authors' professional opinion, research should not only emphasize increasing productivity but should also examine crop quality, especially how to improve crop flavor, sensory attributes, and postharvest longevity. This will increase potential for CE producers to grow and market a premium crop, creating opportunities for increasing profitability (Bi et al., 2012). Additionally, much recent research has focused on lighting technology, including LEDs and the effects of light spectrum (Mitchell et al., 2015). However, growers rated creation of production recipes as equally important. Although more difficult to research than light spectra in isolation, research on how environmental parameters and cultural practices interact will likely lead to more effective production strategies, taking both yield and plant quality into account. However, as interactions become more complex, data interpretation, analysis, and implementation will as well (Boote et al., 1996). Some hydroponic production models exist for CE produced lettuce such as the NiCoLet model predicting nitrate concentrations and growth (Seginer et al., 1998), a modified SUCROS87 model (Spitters et al., 1989) to simulate the effects of DLI, ADT, and plant density on lettuce (Both, 1995), and an evapotranspiration prediction model based on CO_2 and DLI (Ciolkosz et al., 1998). Additionally, many researchers have focused on modeling to determine biomass production without considering crop quality (Marcelis et al., 1998), an aspect of production that is increasingly important (Sadílek, 2019). Finally, although hydroponic nutrient solution research has been conducted for years, it has become clear that, as Hoagland and Arnon (1950) stated: "There is no one composition of nutrient solution which is always superior to every other composition." Increased efficiencies can be realized in nutrient management by investigating the interaction of specific nutrient concentrations and the proportions relative to each other to determine what is necessary for both optimal growth and quality of the range of species grown commercially (Ahn, 2019).

Taken together, multiparameter research working toward optimizing environmental (light quality, quantity, temperature, etc.) and cultural (nutrient solution, cropping duration, etc.) parameters is integral to improving CE hydroponic production. The "optimization" of these parameters is dependent on production goals, which have traditionally focused on improving yield; however, as apparent from this research, many producers are now also focusing on improving crop quality. Therefore, the "optimization" of growing parameters should take both productivity and quality into account.

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