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Trends, Insights, and Future Prospects for Production in Controlled Environment Agriculture and Agrivoltaics Systems

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Abstract

Investments in alternative food production systems by public and private entities have increased in recent years. Two systems, controlled environment agriculture (CEA) and agrivoltaics (AV), have been highlighted for their potential to provide socioeconomic benefits beyond food production. CEA is the use of enclosed structures—including hydroponic and vertical farming structures—for growing crops, primarily specialty crops. CEA may provide access to local production of nutritious food in communities that lack space for traditional outdoor production, improve access to local foods in urban areas, and serve as a potential tool for adapting to or mitigating climate change. The CEA sector is expanding in large part due to technological advancements. The number of CEA operations more than doubled between 2009 and 2019. Further, more than 60 percent of production for some prominent CEA crops (primarily vegetables) were grown using nontraditional technological systems in 2019. AV is the colocation of agricultural production and solar panels. AV may allow for expanded solar development to address climate change without land use conflicts associated with traditional large-scale solar developments. As of 2021, most AV sites were solar farms planted with pollinator-friendly vegetative cover that, in some cases, were grazed by sheep. Funding for research on a variety of AV systems with specialty crop and/or livestock production continues to increase.

Keywords: controlled environment agriculture, CEA, hydroponics, aquaponics, aeroponics, vertical agriculture, agrivoltaics, horticultural crops, renewable energy, greenhouse production, solar energy, solar development

About the Authors

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What Is the Issue?

Public and private investments in alternative food production systems, such as controlled environment agriculture (CEA) and agrivoltaics (AV), have increased in recent years. CEA consists of crop production systems in greenhouses or other structures that use horticultural and engineering techniques beyond conventional soil-based outdoor production. These systems may increase yields, improve access to local foods, provide year-round food access, and/or improve nutritional outcomes relative to traditional large-scale outdoor farming. Additionally, CEA may provide climate change adaptation benefits by reducing the risk of crop failure in more extreme weather relative to traditional outdoor systems. AV is the colocation of solar panels and agricultural production. AV is designed to provide the climate change mitigation benefits of traditional large-scale solar developments while reducing land use competition with agricultural production. Though these systems face technological and economic challenges, the systems are part of a long history of technological advancement in the U.S. agricultural sector. While the systems are unlikely to displace more conventional and larger scale production in the near future, they may increase the supply of locally grown food for some communities and generate climate change benefits, including renewable energy.

What Did the Study Find?

Traditional greenhouses are an established production system. However, innovations in how crops are produced, including hydroponics and vertical agriculture, have led to growth in production and investment in the public and private sectors. AV systems are an emerging technology without a well-established commercial presence, but there is growing public and private investment in research and development. The main findings include:

- The amount of specialty crop production with CEA systems is small compared to outdoor production, but the number of individual CEA operations more than doubled to nearly 3,000 between 2009 and 2019.
- The quantity of crop production increased by 56 percent over that same period, from 502 million pounds to 786 million pounds.

- The aggregate sales value for CEA crops rose from $296 million in 1998 to $769 million in 2014 (in inflation-adjusted terms) but declined to $626 million in 2019 due to declines in the sales value of the dominant CEA crops (particularly tomatoes). This number is likely partly due to increased competition from imports, putting downward pressure on the value of sales per unit.

- Additionally, new technologies were used to produce a large share of total CEA production, with more than 60 percent of tomatoes, cucumbers, and lettuce grown using hydroponics in 2019.

- Recent U.S. Department of Agriculture (USDA) funding to support research and commercialization of CEA systems has increased substantially, including the awarding of contracts and grants exceeding $50 million since 2022 through USDA's Office of Urban and Innovative Agriculture, Agricultural Research Service, and National Institute of Food and Agriculture.

- As of 2021, most of the approximately 300 AV sites were solar farms planted with pollinator-friendly vegetative cover. Roughly 35 sites combined solar panels with vegetation that were grazed by sheep, and a few were co-located with specialty crop production, including blueberries.

- Research sites evaluating a variety of other AV systems with specialty crop and/or livestock production have been established, including several projects funded by the U.S. Department of Energy, Office of Energy Efficiency & Renewable Energy, Solar Energy Technologies Office (DOE-SETO), which has been funding AV research since 2015. This funding included $7 million for AV research awarded in November 2020 for the colocation of pollinator-friendly vegetation, specialty crop production, and livestock grazing with solar panels.

How Was the Study Conducted?

This report uses data from the 2017 USDA Census of Agriculture (COA) and Censuses of Horticultural Specialties (CHS). Specifically, to analyze the market for CEA, the authors used the protected culture statistics from the CHS in 1998, 2009, 2014, and 2019.* For historical information, the authors used Horticultural Specialties Reports from the COA, which is typically conducted every 5 years for the period 1890–1994. For general information on the market for specialty crops, the authors used data from the USDA's National Agricultural Statistics Service (NASS) COA and Vegetable Annual Summary Reports for 1998–2019. Also included is information from the U.S. Department of Energy's list of funded solar research projects and extensive literature reviews.

* The authors included 1998 in the Census of Horticultural Specialties (CHS) years instead of 1997. USDA refers to it as the 1997 CHS, but the data were collected for the 1998 calendar year.

Trends, Insights, and Future Prospects for Production in Controlled Environment Agriculture and Agrivoltaics Systems

Introduction

Growth in U.S. agricultural production has been driven by technological innovations in food development, production, and distribution. These innovations affect the seeds farmers plant, the fertilizers and nutrients farmers apply, how farmers apply them, and how crops are harvested. Some of the technological advancements in crop production (particularly specialty crop production) have focused on addressing socioeconomic concerns, including nutritional security, addressing environmental concerns (particularly climate change mitigation and adaptation), and supporting equity in the production and distribution of food.[1]

This report focuses on two production systems:

(1) Controlled environment agriculture (CEA), which is well established but undergoing a shift with the incorporation of innovative technological solutions, and

(2) Agrivoltaics (AV), a new technological system that has only recently expanded in the United States.

In the United States and elsewhere, food producers, researchers, and entrepreneurs have been creating, experimenting with, and expanding CEA and AV. Controlled environment systems are those production systems in greenhouses or other structures that use horticultural and engineering techniques beyond conventional soil-based, outdoor production. AV is the colocation of solar panels and agricultural production. CEA systems allow specialty crops to be produced in a wider variety of geographic locations and seasons, which may enhance opportunities for the residents of nearby communities to purchase fresh, nutritious foods. CEA systems may also improve crop quality and reduce some of the risks inherent in conventional agricultural systems. AV systems are designed to address concerns over land-use competition, e.g., between farmland and solar infrastructure, and expand renewable energy generation to address climate change while supporting food production.

This report focuses on developments in the United States. However, other countries (such as the Netherlands, Canada, and Mexico) have made significant advancements in CEA production, surpassing the United States in certain aspects. The Netherlands is a leading agricultural exporter, with a small land base that has well-established CEA production systems. Similarly, Davis & Lucier (2021) reported Canada and Mexico are continuing to expand their CEA-grown vegetable production and exports to the United States. Mexico accounted for 81 percent of total greenhouse-grown U.S. vegetable imports (excluding potatoes) during 2018–20. The import volume of CEA-grown fresh-market vegetables from Mexico increased 109 percent

[1] In announcing the establishment of a Federal Advisory Committee on Urban Agriculture, U.S. Secretary of Agriculture Thomas J. Vilsack noted, "urban agriculture has been growing in impact and importance, and we are taking bold action to build a support structure. I look forward to learning how we can better serve urban agricultural producers, which will complement our efforts focusing on equity, local food systems, access to safe and nutritional food, and new ways to address climate change" (USDA, 2022c).

from 2008–10 to 2018–20, while imports of field-grown, fresh-market vegetables increased more slowly by 58 percent. Further, CEA-grown fresh vegetable imports from Mexico during 2018–20 represented almost a third of the total volume of fresh vegetable imports.

In the United States, CEA systems have generally been used to produce tomatoes, cucumbers, greens (such as lettuce and microgreens), and some berries. The systems are often, but not exclusively, entirely enclosed systems with energy and nutrients typically provided within an indoor structure such as a greenhouse. Crops can be grown without soil (in hydroponic systems) or in vertical layers (often known as vertical agriculture systems) with nutrient, climate, and energy sources such as artificial lighting carefully controlled.[2] Agrivoltaics incorporate solar panels with grass or pollinator habitats, specialty crop production, and/or grazing (such as sheep). These systems are typically in an open field, but solar panels can also be incorporated into greenhouse production.

Controlled environment agriculture has largely been initiated as private sector ventures but recently has been increasingly supported by U.S. Department of Agriculture funding and collaborative efforts between USDA and other agencies. Agrivoltaics is supported by a significant amount of research and investment because of its promise in addressing climate change through its colocation of renewable energy production with agricultural production. Understanding the potential benefits of agrivoltaics for generating renewable electricity and addressing climate change is a USDA research priority (USDA, 2023).

In this study, the authors examined recent innovations in the production process for both systems, the extent to which the systems have been adopted, whether the systems are providing output for agricultural markets, and the types of crops or other agricultural goods the systems supply. There have been growing investments in these systems, both for commercial and research purposes. But the growth opportunities also come with economic, technical, and other challenges, which the authors examine in this report.

Controlled Environment Agriculture: Trend Analysis

Controlled environmental agriculture (CEA) is used to describe several different specialty crop production systems in greenhouses or other structures that use horticultural and engineering techniques beyond conventional soil-based, outdoor production. These systems include traditional greenhouses, vertical agriculture, hydroponics, aquaponics, and other indoor production methods. Motivations to adopt CEA food systems include optimizing crop yields, improving crop quality, reducing the risks inherent in conventional agricultural systems, and/or extending harvest periods for crops by controlling temperature, wind, lighting, precipitation, and/or most pests.[3]

USDA's 2017 Census of Agriculture (COA), the most recent available, includes information on the dollar value of sales for specialty crops produced with traditional outdoor production. In 2017, U.S. farms sold just over $21.6 billion worth of vegetables in constant or real (2012) dollars, including melons, potatoes, sweet

[2] Greenhouses are traditional controlled environmental agriculture (CEA) structures that either cover or enclose crops and have been made of various materials such as cloth, glass, and plastic. Many greenhouses use natural sunlight and supplement with artificial lighting, while entirely enclosed CEA structures exclusively use artificial lighting.

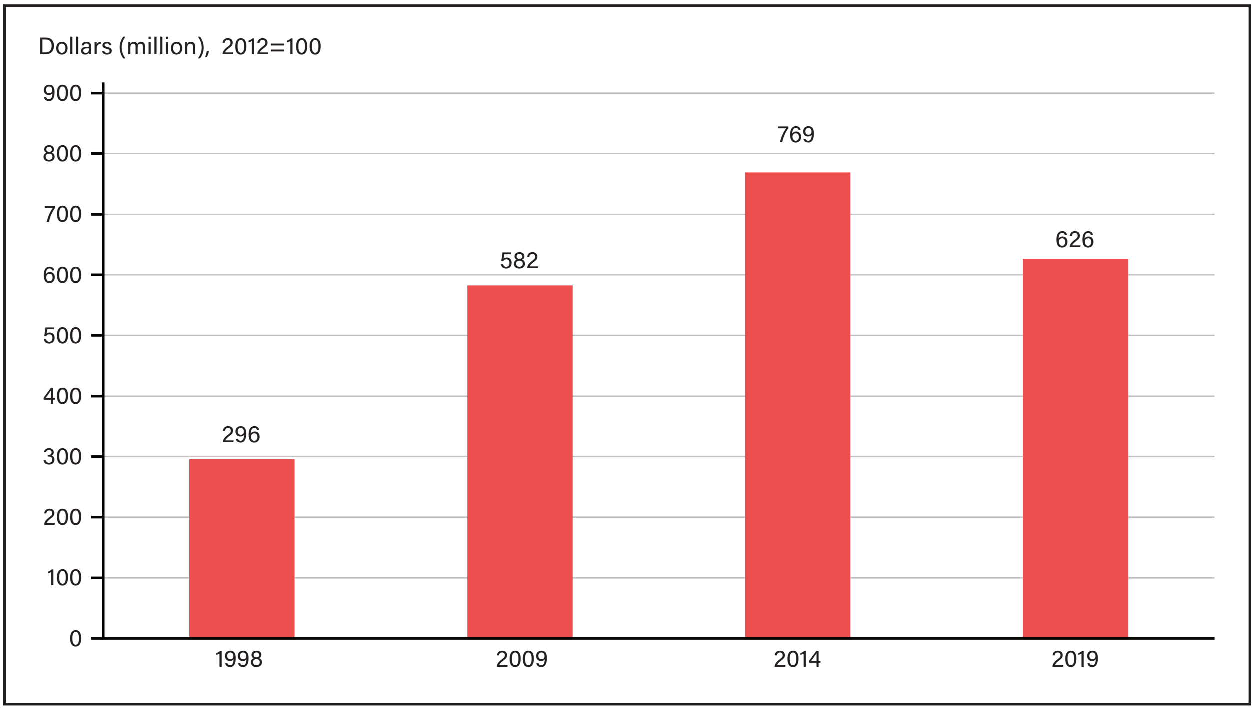
[3] Controlled environment agriculture is also referred to as protected agriculture or protected culture. These terms have been used in USDA, National Agricultural Statistics Service reports since 1998. Prior to 1998, the terms greenhouse or "under glass or other protection" were frequently used.

potatoes, and berries—not including crops produced in CEA.[4] For comparison, the Census of Horticultural Specialties (CHS) includes information on specialty crops produced using CEA. In 2019, the total value of sales for crops grown with CEA was $626 million in constant or real (2012) dollars. While CEA sales values are not directly comparable to COA sales values, the data suggest that the value of food crops grown with CEA comprises a small share of the total value of specialty crop production.[5]

Figure 1 presents sales values for all food crops for each CHS year from 1998 to 2019 in constant (2012) dollars. The total value of sales of all CEA food crops (in inflation-adjusted terms) was estimated to be $296 million in 1998, increasing to $769 million in 2014 before falling to $626 million in 2019.

Figure 1

U.S. sales of controlled environment agriculture-produced food crops, 1998, 2009, 2014, and 2019 (inflation adjusted dollars)



Note: Includes total wholesale and retail sales of cucumbers, fresh cut herbs, lettuce, peppers, strawberries, tomatoes, and all other, unspecified food crops grown under protection (controlled environment agriculture food crops). Constant dollar values were calculated using the gross domestic product implicit price deflator, 2012=100. Years represent calendar year sales, except for a small number of operations that maintain their records on a fiscal year basis.

Source: USDA, Economic Research Service calculations using data from USDA, National Agricultural Statistics Service, *Census of Horticultural Specialties*, 1998–2019.

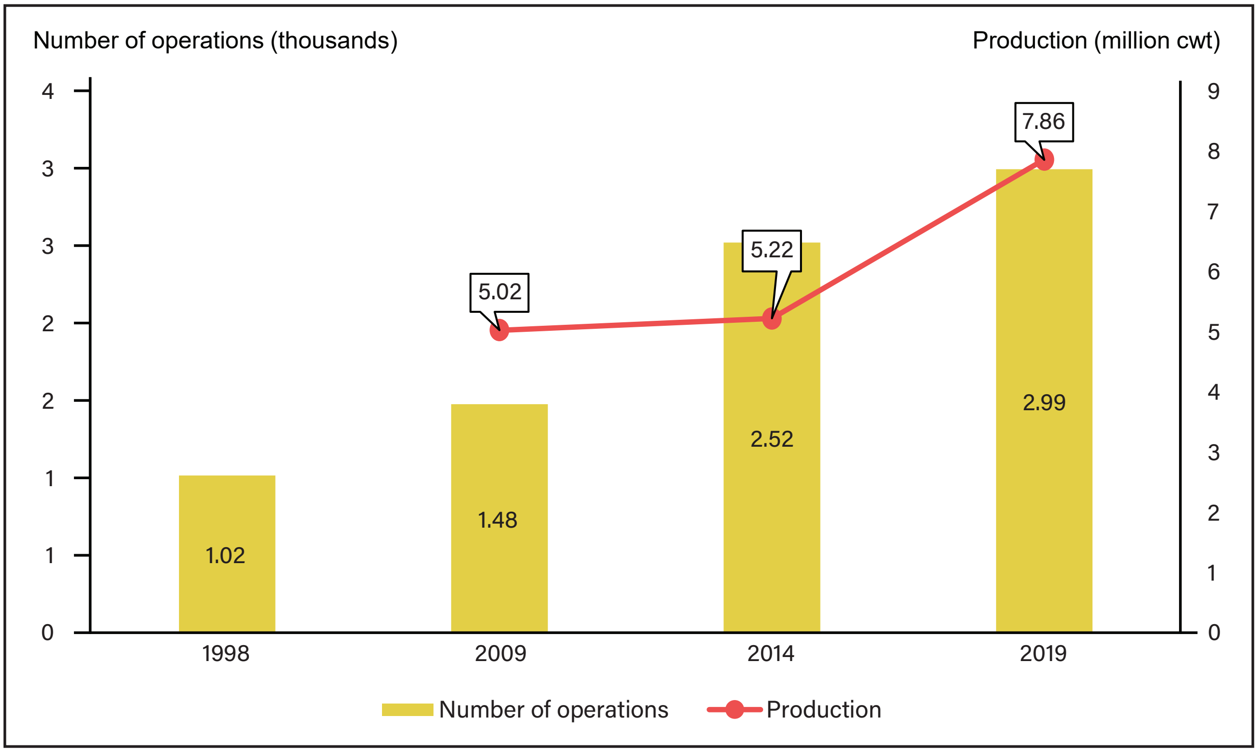
[4] The COA includes some information on CEA crops (including the number of farms, acres, sales, and area), but the COA is aggregated by crop type (e.g., vegetables). The COA includes crop-specific CEA data only for tomatoes and mushrooms (USDA, NASS, 2019). To better compare the constant (or real) value of production spanning the 1998–2019 time period, we select 1 year (2012) as the base period.

[5] CHS data on food crops grown with CEA are not directly comparable with COA data on specialty crops. The data are collected in different years, and there are differences in the statistics collected and the collection methods (USDA, NASS, 2020).

Over the same period, however, the number of CEA operations almost tripled—from 1,015 in 1998 to 2,994 in 2019 (figure 2). The increase in operations is, not surprisingly, associated with an increase in production, from 5.02 million hundredweight (cwt) in 2009 to 7.86 million cwt in 2019.[6] Despite falling aggregate sales values, the CEA sector has been expanding over this period. An increase in the number of operations and overall production (combined with falling sales values) is due to declines in sales values for the more predominant food crops, which exceeded increases for crops that comprise a smaller share of CEA production.

Figure 2

U.S. controlled environment agriculture operations and production, 1998, 2009, 2014, and 2019



cwt = hundredweight.

Note: Includes commercial controlled environment agriculture (CEA) operations that reported sales of $10,000 or more by calendar year, except for a small number of operations that maintain their records on a fiscal year basis. CEA production statistics were not reported in 1998.

Source: USDA, Economic Research Service using data from the USDA, National Agricultural Statistics Service, *Census of Horticultural Specialties*, 1998–2019.

There has been less expansion of the CEA sector in the United States compared to some other countries due to several factors, including relatively high costs as compared to traditional outdoor production. This is partly due to persistent high costs in construction materials (mostly glass), labor, and energy investments for the controlled temperature and lighting used to operate these structures (Stein, 2021). In the mid-1960s, the use of various forms of plastic lowered material costs and provided more opportunities for CEA domestically (Teitel et al., 2018). The steady development and more widespread adoption of light emitting diodes (LEDs) led to a decrease in the cost of supplemental lighting, which is used to optimize photosynthesis (Van Iersel, 2017). The adoption of additional technological advancements, including solar panels, could further decrease electricity costs (Mohareb et al., 2017).

[6] One hundredweight (cwt) is equal to 100 pounds.

Although CEA and traditional greenhouses have a long history, technological innovations in crop production and new systems (including hydroponics) are more recent additions to the sector. Partly due to the promise of CEA to address local socioeconomic concerns, including providing nutritious food in local communities that do not have soils or weather conditions to support traditional agricultural production, investment in CEA is expanding, and research is underway to improve yields while also lowering costs. USDA provides technical support for CEA, with research led by the USDA, Agricultural Research Service (ARS) Greenhouse Production Research Group (GPRG), several other USDA, ARS research units and programs, collaborations with industry partners, and financial support through USDA, ARS and several other USDA agencies.

USDA Research Support for Controlled Environment Agriculture

In the last several years, the U.S. Department of Agriculture (USDA), sometimes in collaboration with other Federal agencies, including the U.S. Department of Energy (DOE) and the National Aeronautics and Space Administration (NASA), has launched new initiatives to further research on various aspects of controlled environment agriculture (CEA) systems. This includes research to increase the productivity, economic viability, and development and marketability of CEA crops. The USDA supports a number of programs, some long-standing and others newly formed. Some examples are:

- The USDA, Agricultural Research Service's (ARS) Greenhouse Production Research Group (GPRG) conducts a long-standing agronomic research program for evaluating crop response to various technological aspects of greenhouse production, including lighting, temperature, humidity, carbon dioxide supplantation, and pest management. GPRG's goal is to transfer technological innovations to industry.

- USDA, ARS has awarded multiple contracts to a private agricultural technology company (AmplifiedAg) to supply integrated vertical farming research labs to support the agency's CEA research initiatives. The company's work will be devoted to examining CEA expanding applications, including hydroponic and vertical farming, light emitting diodes (LED) light spectrum impact analysis on plant growth, nutrient optimization, and plant breeding. As part of the USDA, ARS "Grand Challenge Synergies Project" on CEA production, USDA, ARS has contracted with AmplifiedAg to acquire fully integrated containerized vertical farms for research purposes. The research is intended to standardize growing methods for indoor farming operators and includes the following priority objectives for supporting CEA production: (1) genetics and breeding of new/adapted varieties; (2) energy efficiency and LED lighting sources; (3) growth media, hydroponics, and aquaponics; (4) integrated pest management and pollinator health; and (5) improve food quality, safety, and nutrition.[1]

- USDA, ARS has also begun collaborative discussions through workshops on CEA, including one held with the Lawrence Berkeley National Laboratory (representing research by the DOE), NASA, and the University of Toledo in November 2021 (Altland et al., 2021). A follow up multi-agency workshop (hosted by USDA, ARS and held in Toledo, Ohio in June 2023) gathered more than 150 participants from public research institutions and the private industry to discuss how to advance controlled environment agriculture on land and in space in the next 20 years. The workshop covered several topics, including (1) emerging technologies in sensing, automation, artificial intelligence, machine learning, and control, (2) water efficiency and management, (3) plant breeding and adaptations to controlled environments, (4) pest management and plant health,

[1] Joseph Munyaneza, national program leader, Vegetable Sugarbeet, and Greenhouse Crops, USDA, Agricultural Research Service (personal correspondence, March 6, 2023).

(5) food quality, safety, and nutrition, (6) economics, hurdles to adoption, and societal impacts, and (7) Federal funding opportunities. Similarly, USDA, ARS hosted CEA outreach workshops are planned to be held every year.

- The Office of Urban Agriculture and Innovative Production (OUAIP), led by USDA's Natural Resources Conservation Service (NRCS), provides technical and financial support for hydroponic and vertical production systems, among others, in urban and suburban areas.[2] Press releases[3] announced rounds of funding by this office:
  - On June 3, 2022, USDA announced $43.1 million in new grants, including $14.2 million in new grants to support the development of urban agriculture and innovative production projects.
  - On October 26, 2022, USDA announced $14.2 million in funding for 52 grants in 27 States. The announcement notes that the new funding builds on $26.3 million in projects funded since 2020 through the OUAIP.
  - On January 26, 2023, USDA announced another $7.5 million for grants through OUAIP to support innovative production projects through two categories: planning and implementation.

Separately, the USDA, National Institute of Food and Agriculture (NIFA) announced in February 2023 that as part of $70 million in new funding for sustainable agricultural projects, Auburn University will receive a $9.95 million grant to support CEA research intended to reduce the demand for heating and cooling in CEA food-production environments, improve the overall efficiency of CEA climate-controlled environments, lower the carbon intensity of resource inputs, and shift consumer and producer behavior surrounding CEA products and practices.[4] In addition, other USDA agencies provide resources that can support urban and innovative agricultural production.[5] Examples include:

- USDA, NRCS offers financial assistance and free guidance for conservation practices, including high and low tunnels (plastic- or fabric-covered structures used to extend growing seasons) and soil health management.
- USDA, Farm Service Agency provides microloans that can be appropriate for the unique needs of urban farms.
- USDA, Rural Development provides loans to intermediary lenders who provide guaranteed loans to individuals for infrastructure and other needs.
- USDA, NIFA offers grants for technical assistance initiatives for beginning farmers.

[2] The Urban Agriculture and Innovative Production (UAIP) Competitive Grants program is authorized by Section 222 of the Department of Agriculture Reorganization Act of 1994, as added by Section 12302 of the Agriculture Improvement Act of 2018, 7 U.S.C. 6923. Funding was made available by the American Rescue Plan Act of 2021, Public Law 117–2.

[3] USDA press release Number 0121.22 (June 3, 2022), USDA press release Number 0228.22 (October 26, 2022), and USDA press release Number 0017.23 (January 26, 2023).

[4] USDA, NIFA press release, February 9, 2023.

[5] USDA "Urban Agricultural Programs at a Glance" (October 2022b).

Controlled Environment Agriculture: Crop Specific Analysis

Published estimates of CEA crop production have been available for a short list of produce (cucumbers, lettuce, tomatoes, peppers, herbs, and strawberries) for well over a century.[7] In fact, the first estimates of greenhouse production, as well as a brief description of the local market for specialty crops in New England, were published in the 1890 Census of Agriculture: Horticulture - Truck Farming.[8] The Census indicates that delicate or tender greenhouse vegetables were produced in New England with CEA in the early winter and spring when it was too cold for traditional outdoor production.

At the time, these vegetables had to be produced locally due to their perishability and could not be transported from warmer production regions such as California. This allowed farmers to profit from selling the vegetables despite the higher costs of producing them using CEA. This anecdote from the Census provides an early example U.S. consumer demand for premium-priced vegetables grown with CEA in cold seasons when crops grown with traditional agricultural production were unavailable.

To explore trends for specific crops produced with CEA, the analysis focuses on a recent period, from 1998 to 2019, because CHS estimates are based on a consistent set of definitions beginning in 1998. The CHS provides estimates of area, number of farm operations, amount of production, and the value of sales for the six specialty crops listed above (and an unspecified, all other food crops category).

Controlled Environment Agriculture: Area

CEA crop area is the physical land area used in greenhouses or shade structures for specific crops grown during a growing season.[9] USDA, National Agricultural Statistics Service (NASS) measures crop area through surveys and satellite imagery and reports crop area in square feet. Over the census years of 1998, 2009, 2014, and 2019, tomatoes averaged 53 percent of the total CEA-produced food crops area, with a much smaller share devoted to all other food crops. For instance, the 1998 CHS reported that almost 55 percent of the total area (in square feet) in CEA food production was devoted to tomatoes, nearly 15 percent to fresh-cut herbs, about 10 percent to cucumbers, nearly 5 percent to peppers, about 4 percent to lettuce, less than 1 percent to strawberries, and another 12 percent to other unspecified food crops. In 2019, about 59 percent of the total area was devoted to tomatoes, 12 percent to fresh-cut herbs, 7 percent to cucumbers, 6 percent to lettuce, almost 3 percent to peppers, nearly 1 percent to strawberries, and another 12 percent for other unspecified food crops.

The stability in the relative area used across the set of specialty crops in 1998 and 2019 masks crop variability that occurred between 2014 and 2019 (figure 3). The crop area declines in cucumbers, herbs, peppers, and

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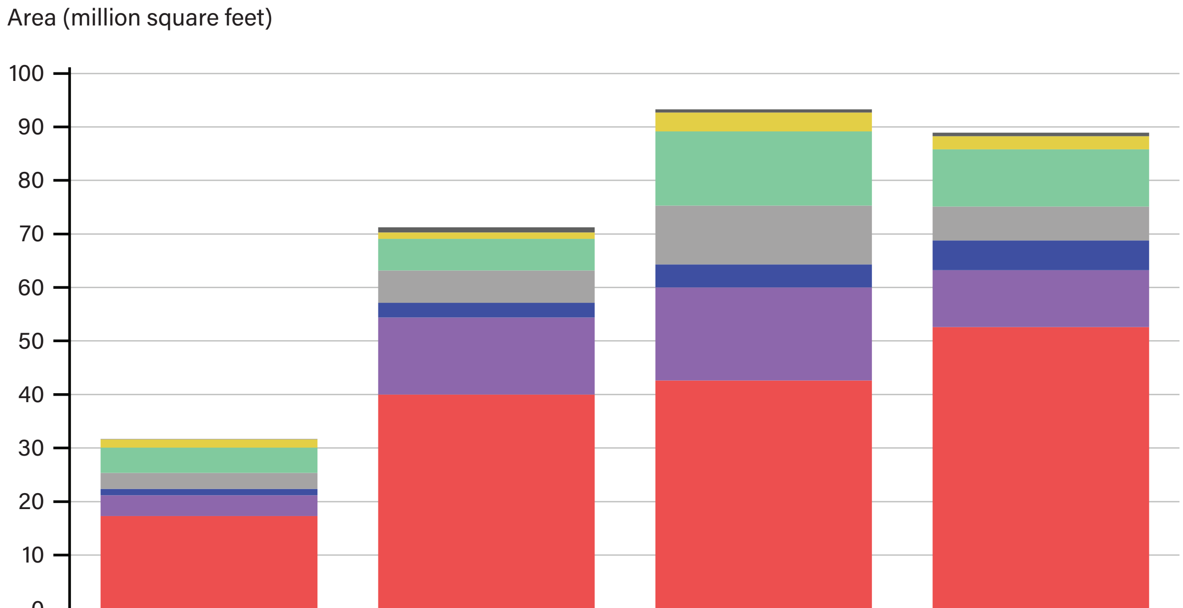
[7] Mushrooms, which are grown indoors but not in greenhouses, were historically included in some years in the Census of Agriculture data on specialty crops but have not been included as part of the Census of Horticultural Specialties since 1998 because more detailed information about mushroom production is now included as part of NASS' annual mushroom survey that serves as a Census of all U.S. mushroom growers (see 2017 Census of Agriculture, appendix B).

[8] From 1840 to 1996, the data for what became known as the Census of Agriculture were collected by the Bureau of the Census, which was originally within the U.S. Department of the Interior. Eventually, this department was transferred to the Department of Commerce and Labor in 1903 before subsequently being renamed the U.S. Department of Commerce in 1913. Initially, agricultural data were collected as part of the decennial population censuses. In 1997, USDA's National Agricultural Statistics Service (NASS) began collecting data for the Census of Agriculture, which has been conducted every 4 or 5 years since 1920 and every 5 years since 1982. USDA, NASS also collects data for other national surveys and censuses, including the Census of Horticultural Specialties, which has been conducted 11 times since 1889 (most recently in 1998, 2009, 2014, and 2019). For the 1890 Census reports on protected culture (which reports data collected in 1889), see U.S. Department of the Interior, Bureau of the Census. U.S. Census of Agriculture: 1890, Horticulture - Truck Farming.

[9] The area used for production also includes the area on benches or other stacked arrangements on which crops were grown. For example, if crops were grown in stacked trays three tiers high, the square footage of each tier was multiplied by the number of tiers to arrive at the area used for production.

all other unspecified food crops during 2014–19 outweighed the increasing crop area in strawberries, lettuce, and tomatoes by 5 percent. From 2014 to 2019, food crop area in CEA declined for cucumbers (from nearly 11 million square feet to 6.34 million square feet), herbs (13.85 million square feet to 10.69 million square feet), peppers (3.52 million square feet to 2.48 million square feet), and all other unspecified food crops (17.38 million square feet to 10.67 million square feet), while the area increased for strawberries (620,000 square feet to 660,000 square feet), lettuce (4.33 million square feet to 5.53 million square feet), and tomatoes (42.60 million square feet to 52.58 million square feet).

Figure 3
U.S. area of total controlled environment agriculture food crops, 1998, 2009, 2014, and 2019



	1998	2009	2014	2019
Strawberries	0.04	0.94	0.62	0.66
Peppers	1.51	1.23	3.52	2.48
Herbs, cut fresh	4.73	5.93	13.85	10.69
Cucumbers	3.02	6.01	11.00	6.34
Lettuce	1.17	2.75	4.33	5.53
All other food crops	3.88	14.42	17.38	10.67
Tomatoes	17.31	39.96	42.60	52.58

Note: Years represent calendar year area values, except for a small number of operations that maintain their records on a fiscal year basis.

Source: USDA, Economic Research Service using data from the USDA, National Agricultural Statistics Service, *Census of Horticultural Specialties*, 1998, 2009, 2014, and 2019.

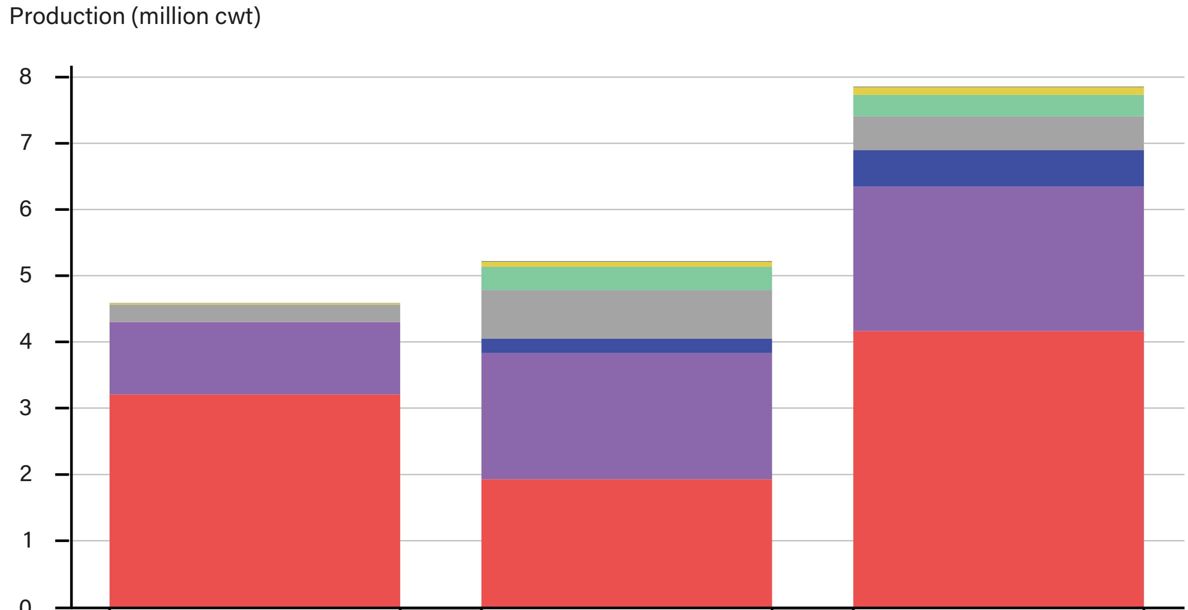
Controlled Environment Agriculture: Production

To examine shifts in the composition of CEA food crops, figure 4 includes crop production estimates from CHS from 2009 to 2019.[10] USDA, NASS uses a variety of methods to estimate crop production such as

[10] Production is the total quantity harvested of a specific crop.

producer surveys, yield estimates, and analyses of required administrative data collected from producers. CHS reports the amount of production in hundred-pound units, also known as hundredweight (cwt).

Figure 4
U.S. production of controlled environment agriculture food crops, 2009, 2014, and 2019



	2009	2014	2019
Strawberries	0.004	0.007	0.012
Peppers	0.018	0.077	0.111
Herbs, cut fresh	-	0.355	0.326
Cucumbers	0.265	0.726	0.510
Lettuce	-	0.219	0.552
All other food crops	1.094	1.909	2.180
Tomatoes	3.207	1.925	4.166

cwt = hundredweight.

Note: Years represent calendar year production, except for a small number of operations that maintain their records on a fiscal year basis. Production in calendar year 2009 for lettuce and fresh-cut herbs was not disclosed.

Source: USDA, Economic Research Service using data from the USDA, National Agricultural Statistics Service, *Census of Horticultural Specialties*, 2009, 2014, and 2019.

In 2009, total production of all CEA food crops (including all other, unspecified food crops) was 5.023 million cwt and rose by 56 percent to 7.856 million cwt in 2019 (figure 2).[11] Overall production increased, but trends varied by crop between 2014 and 2019 (figure 4). There were production increases in lettuce (up 152 percent to 552,000 cwt), peppers (up 67 percent to 111,000 cwt), strawberries (up 67 percent to 12,000 cwt), tomatoes (up 116 percent to 4.166 million cwt), and all other, unspecified food crops (up 14 percent to 2.180 million cwt). Conversely, production decreased for cucumbers (down by 30 percent to 510,000 cwt) and herbs (down by 8 percent to 326,000 cwt). Although changes in crop production and area were gener-

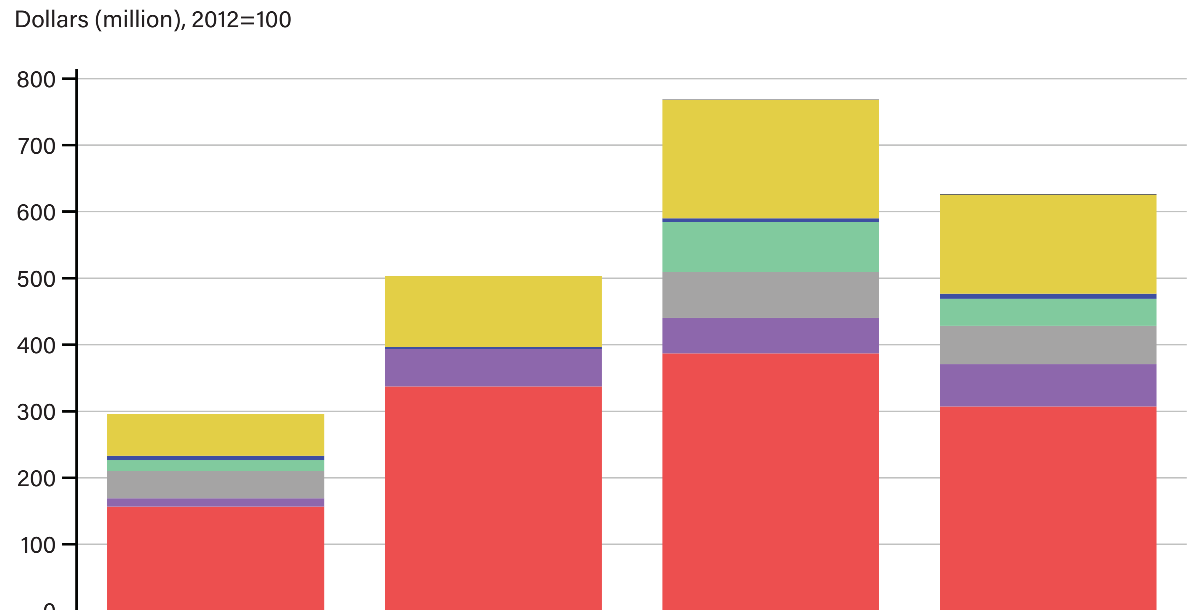
[11] CEA production statistics were first reported in 2009. The CEA statistics published prior to 2009 were the number of CEA operations, area, and sales.

ally consistent (i.e., both declined or both increased), pepper production increased while the area declined. Production increases with crop area declines are typically attributed to higher yields per crop.

Controlled Environment Agriculture: Sales Value

To further examine trends by crop, figure 5 includes the sales value of individual crops. For context, the total real value of farmgate sales of all CEA food crops (including all other, unspecified food crops) was estimated to be $296 million in 1998 and rose to $769 million by 2014 before falling to $626 million in 2019 (figure 1). All constant-dollar (inflation adjusted) values are reported in 2012 dollars.

Figure 5
Farm value of sales of controlled environment agriculture food crops produced, 1998, 2009, 2014, and 2019



	1998	2009	2014	2019
Strawberries	0.1	0.6	0.9	0.8
All other food crops	62.3	106.7	178.0	148.6
Peppers	7.0	2.3	5.8	7.6
Cucumbers	16.2	-	74.9	40.7
Herbs, cut fresh	41.2	-	68.4	58.0
Lettuce	12.4	56.7	53.6	63.3
Tomatoes	156.6	337.3	387.1	307.2

Note: Includes total wholesale and retail sales of cucumbers, fresh-cut herbs, lettuce, peppers, strawberries, tomatoes, and all other, unspecified food crops under protection. Constant dollar values were calculated using the gross domestic product implicit price deflator, 2012=100. Years represent calendar year sales, except for a small number of operations that maintain their records on a fiscal year basis. Farm value of sales in calendar year 2009 for cucumbers and fresh-cut herbs was not disclosed.

Source: USDA, Economic Research Service calculations using USDA, National Agricultural Statistics Service, *Census of Horticultural Specialties*, 1998–2019.

CEA tomato area and production increased from 2014 to 2019, while the value of CEA tomato sales decreased from nearly $387 million to $307 million in real terms (figure 5). These changes indicate that the per unit value for CEA-produced tomatoes decreased. The observed downturn in sales value aligns with the trends illustrated in figure 1, showing the overall sales value of CEA declined during this same period. The cumulative decrease in tomato, cucumber, herb, and strawberry sales value outweighed the 32-percent increase in peppers during that same period. Specifically, tomato sales values fell by 21 percent, cucumber values were down 46 percent, herbs values were down 15 percent, and strawberries declined by 6 percent. With the rise in CEA tomato production, it is plausible that this contributed to the downward pressure on prices, which resulted in the decline in overall sales values for CEA specialty crops. Specifically, the decline in sales value for tomatoes and cucumbers can be partly attributed to an increase in imported produce putting downward pressure on domestic prices, which has dampened incentives to expand U.S. CEA production for some specialty crops (Davis & Lucier, 2021).[12]

Controlled Environment Agriculture: Dollar Value per Unit

To examine dollar value per unit trends of CEA crops and traditional field-grown crops, figure 6 includes measures of the sales value per unit (dollars per cwt) constructed using total sales and production data from the CHS for CEA crops in the years 2009, 2014, and 2019. Figure 7 includes reported dollars per cwt values from the USDA, NASS Vegetables Annual Summary, published in the corresponding years.[13]

The figures include two crops for comparison—tomatoes and strawberries. For the other four CEA-grown crops (lettuce, herbs, peppers, and cucumbers) surveyed in the CHS, there were missing data either for sales values or production for at least 1 CHS year in the 2009–14 period, or there were crop varietal differences that limit comparison with field-grown crops in the Vegetables Annual Summary publication.[14] As noted previously, tomatoes are the dominant crop grown with CEA each year; strawberries are the only individual fruit crop reported and had the smallest production and sales value. From 2009 to 2019, CEA production increased for tomatoes and strawberries, though CEA tomato production dropped in 2014 before rising in 2019. Tomato sales values rose from 2009 to 2014 before declining in 2019.

The estimates for CEA from the CHS and field-produced crops from the USDA, NASS Vegetables Summary are not directly comparable due to differences in sampling and inherently different marketing channels.[15] The figures and findings should be interpreted with this in mind.

[12] USDA, Economic Research Services's April 2021 Vegetables and Pulses Outlook special article entitled "Import competition in the U.S. fresh vegetable industry" provides an update on the impact rising imports have on the U.S. fresh vegetable industry from 1998–2020, with a focus on four specialty crop markets.

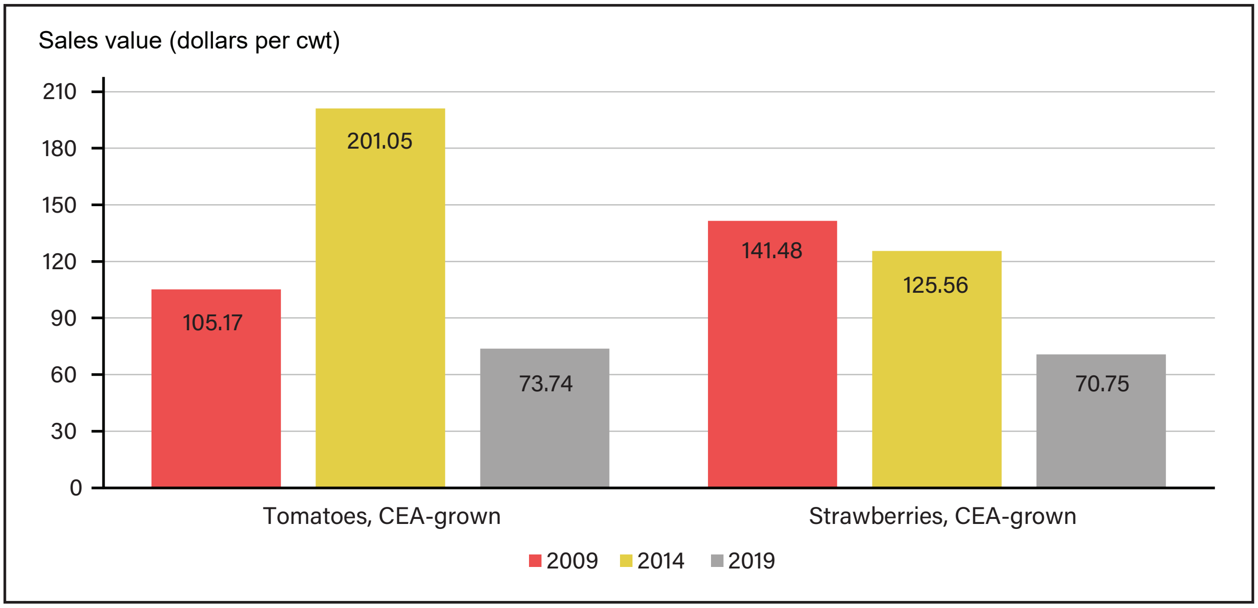
[13] The Vegetables Annual Summary includes annual average price estimates from field-grown specialty crops.

[14] There were also differences in the crop varieties estimated (e.g., peppers in the CHS are reported as a single crop with no variety breakdown), while in the Vegetables Summary, the differences are categorized across two varieties (bell and chili).

[15] The CEA-grown crop sales value estimates from the CHS include both wholesale and retail sales without a similar wholesale/retail breakdown for production. The field-grown marketing year average prices from the Vegetables Annual Summary are the average prices producers receive at the point of first sale with varying marketing channels, which include some vegetables sold free on board (F.O.B.) packed by growers, others sold in bulk vegetables at the packinghouse door, and others are sold retail at roadside stands. The other difference between the CHS and the Vegetables Annual Summary relates to sampling. The CHS sample is comprehensive, designed to include a high sample of States in the contiguous United States, while the Vegetables Annual Summary includes only the top-producing States. Specifically, the annual Vegetables Summary includes 2 producing States (California and Florida), while the 2019 CHS sample includes 36 States for CEA-grown strawberries and 50 States for CEA-grown tomatoes.

Figure 6

Controlled environment agriculture sales value per unit in constant dollars, 2009, 2014, and 2019



cwt = hundredweight. CEA = controlled environment agriculture.

Note: Years represent calendar years, except for a small number of operations that maintain their records on a fiscal year basis. CEA-grown utilization is assumed to include all utilizations (fresh and processed markets). CEA prices per unit are derived using total (wholesale and retail) sales and production data from the Census of Horticultural Specialties and are also converted to constant dollars (2012=100). CEA-grown data include a comprehensive sample of States.

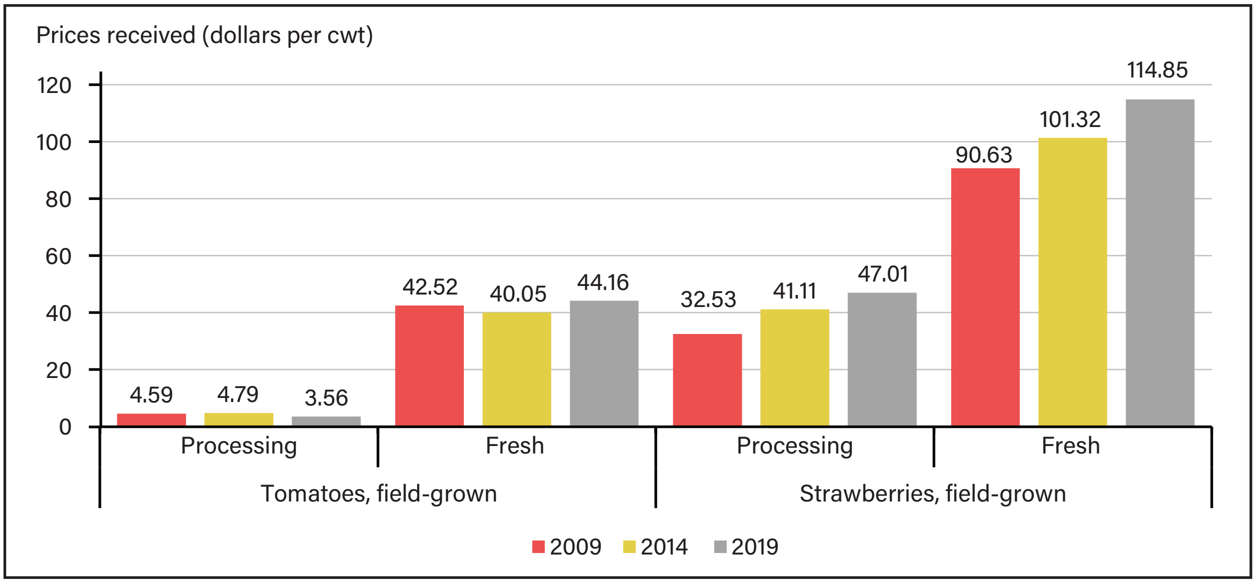
Source: USDA, Economic Research Service calculations using USDA, National Agricultural Statistics Service, *Census of Horticultural Specialties*, 2009, 2014, 2019.

The findings illustrated in figures 6 and 7 vary by crop. Sales value per unit of CEA-grown crops for tomatoes and strawberries during 2009–19 declined, while overall field-grown prices for fresh and processed strawberries increased from 2009 to 2014 to 2019. However, changes in CEA-grown and field-grown tomato prices per unit are mixed during the same period. CEA-grown tomatoes' value per unit in constant dollars rose sharply, increasing by 91 percent to $201.05 per cwt from 2009 to 2014 before declining by 63 percent from 2014 to 2019 to $73.74 per cwt. Average field-grown tomato prices for fresh and processed showed much smaller changes in comparison to CEA-grown value per unit. Processing field-grown tomatoes rose by 4 percent from 2009 to 2014 to $4.79 per cwt before declining in 2019 by 26 percent to $3.56 per cwt. Fresh, field-grown tomatoes declined by 6 percent to $40.05 per cwt before rising by 10 percent to $44.16 per cwt.

Despite previously noted differences in the CHS and Vegetables Annual Summary sourced estimates, the findings suggest that CEA tomatoes and strawberries may not consistently have a higher value per unit over their field-grown counterparts. Differences between CEA and field-grown values per unit vary by crop, and even if the CEA-grown value is higher (as is the case for tomatoes), the magnitude of the difference varied dramatically over this period.[16]

[16] The annual field-grown price data from the Vegetables Annual Summary were limited to the same 3-year period within 2009–14 to align with the years the CEA data are available. However, this limited coverage of field-grown price data may not accurately reflect continuous market variations within each period and could potentially affect the trend analysis for field-grown crops.

Figure 7
Field-grown value per unit in constant dollars, 2009, 2014, and 2019



cwt = hundredweight.

Note: Years represent marketing years. Annual marketing year average prices are converted to constant dollars (2012=100) for both crops. Processing tomato units were converted from dollars per tons to dollars per cwt. Field-grown estimates are limited to the top-producing States.

Source: USDA, Economic Research Service calculations using USDA, National Agricultural Statistics Service, Vegetables Annual Summary, various years.

Controlled Environment Agriculture: Hydroponics

One type of CEA that has experienced market growth between 2009 and 2019 is hydroponics systems, or simply hydroponics. Hydroponics is a broad term referring to any irrigated growing system that does not involve soil. It includes both aquaponics systems—where plants, fish, and other seafood receive nutrients and moisture from irrigation in an integrated system—and aeroponic systems, where plants receive nutrients from aerosols in the air (Somerville et al., 2014).[17] Hydroponic systems (like CEA more broadly) are used to grow vegetables and small fruits such as tomatoes, lettuce, cucumbers, strawberries, and peppers and have the potential to achieve greatly increased food production per unit of inputs than traditional, soil-based, open-field production systems (Gómez et al., 2019).[18] The systems are often designed to facilitate high-density plantings, which can increase the efficiency of input use. For example, the systems often incorporate vertical agriculture, with crops grown in layers or stacked (see appendices A and B for a more detailed technical discussion of hydroponic and aquaponic systems).

The 2009, 2014, and 2019 CHS include estimates of the volume of food crops produced using hydroponics.[19] As a subset of the total volume grown in CEA systems in 2019, a majority of three crops (about 61 percent of tomatoes, 67 percent of cucumbers, and 66 percent of lettuce) were grown in hydroponic systems. For the

[17] Some people distinguish hydroponic systems that use aqueous solutions for irrigation from aeroponic systems that use aerosolized nutrient solutions (e.g., Eldridge et al., 2020). Others consider all soilless systems to be hydroponic systems (Schröder & Lieth, 2002).

[18] Other crops (including wheat) have also been demonstrated to achieve remarkably higher yields in hydroponic systems than in conventional, field-based systems (Asseng et al., 2020). However, the energy requirements for wheat production in hydroponic systems currently make the systems economically infeasible.

[19] Other data included in the CHS on number of producers, greenhouse area, and sales are not broken out by type of CEA system, however.

other specialty crops, hydroponics contributed a smaller share of production—23 percent of fresh-cut herbs, 3 percent of peppers, and 16 percent of strawberries.[20] The overall volume of food crops grown in hydroponic systems increased from about 3.7 million cwt in 2009 to 4.2 million cwt in 2019 (table 1).

Table 1
Controlled environment agriculture and hydroponics production of food crops, number of operations, 2009–19

	2009			2014			2019		
	Production (1,000 cwt)		Number of CEA operations	Production (1,000 cwt)		Number of CEA operations	Production (1,000 cwt)		Number of CEA operations
	All CEA systems	Hydro. systems		All CEA systems	Hydro. systems		All CEA systems	Hydro. systems	
Cucumbers	265	243	343	726	662	733	510	340	1,003
Herbs, fresh	D	D	323	355	76	524	326	74	700
Lettuce	D	D	338	219	154	763	552	364	1,042
Peppers	18	0.6	265	77	D	534	111	3	745
Strawberries	4	0.1	76	7	D	130	12	2	161
Tomatoes	3,207	2,846	1,148	1,925	1,656	1,889	4,166	2,533	2,205
Other food crops	1,094	263	345	1,909	736	851	2,180	905	1,005
Food crops in total	5,023	3,652	1,476	5,219	3,311	2,521	7,857	4,222	2,994

cwt = hundredweight. CEA = controlled environment agriculture.

Note: The "total" row does not reflect the sum of the other rows because some cells are not reported in the Census of Horticultural Specialties (indicated here with "D").

Source: USDA, Economic Research Service using data from USDA, National Agricultural Statistics Service, Census of Horticultural Specialties, 2009, 2014, and 2019.

However, not all crops exhibited the same growth trends within CEA or hydroponic systems. For example, the production of tomatoes in CEA and hydroponic systems declined from 2009 to 2014 before rising again in 2019; cucumber production in CEA and hydroponics rose from 2009 to 2014 before declining again in 2019. Additional research is needed to understand whether changes in production from 2014 to 2019 reflect long-run trends or potential trajectories of growth in the industry.

Controlled Environment Agriculture: Research and Future Growth

Like any industry in an emerging stage, indoor agriculture (particularly fully enclosed systems with no natural lighting) faces many challenges that must be addressed to become a viable and growing long-term contributor to the global agricultural sector. This section considers those challenges (and opportunities) that are broadly applicable to CEA in general but with a focus on newer and more technologically advanced systems, such as hydroponics and vertical agriculture.

CEA, in general, can allow more crop harvests per year (particularly with optimized LED lighting), reduce losses due to weather and pests, and see less spoilage due to being closer to the customer base. In particular, one of the promoted benefits of CEA is increasing output while decreasing the use of some inputs per unit of production or area. For example, table 2 shows yields per square meter per year for several crops based on data from the 2019 CHS, the 2021 Vegetables Annual Summary, and various scientific experiments. Based

[20] Because the CHS does not distinguish production by other types of CEA systems, we presume that the remainder of production is in soil-based greenhouses.

on the two USDA, NASS reports, average yields of strawberries (per unit of area) are about 40 percent higher when grown under protection than when grown in open fields. The increase in yields of other crops when grown under protection is even higher, ranging from 400 percent higher for tomatoes to more than 2,100 percent higher for cucumbers.

The scientific evidence referred to in table 2 mostly demonstrates that CEA systems improve yields because of environmental factors that are favorable for production (including light, temperature, humidity, pH and nutrient concentrations, and improved availability of nutrients and water). For example, Majid et al. (2021) showed that there are notable differences in lettuce crop duration (time from planting to harvest) between conventional cultivation systems and hydroponic systems because of nutrient uptakes. In the soil-based system, it took 48 days to reach maturity and 107 days for the total growing cycle, while the days to maturity and total growing days were 40.5 days and 92.5 days, respectively, in the deep-water culture (DWC) hydroponic system. The nutrient film technique (NFT) hydropic system required 47 days for maturity, and the total growing cycle was 99 days (see appendix A for a discussion of DWC and NFT systems). Moreover, Majid et al. (2021) also examined the differences in yield (kilograms/plant) between the conventional cultivation system and hydroponics (DWC and NFT): 1.15 kilograms in the conventional cultivation system, 1.64 kilograms in the DWC system, and 1.32 kilograms in the NFT system.

Data from the CHS do not necessarily reflect the maximum potential yields per unit of area and may include nonvertical protected agricultural systems, including soil-based and hydroponic systems. As shown in table 2, yields from hydroponic systems have been demonstrated to be even higher in certain scientific experiments. For example, Kowalczyk et al. (2020) achieved cucumber yields approximately 33 times higher than the average open-field yields based on the 2021 Vegetables Annual Summary. However, scientific experiments attempting to achieve maximum yields do not consider the costs of inputs (including management expertise), and it is unlikely that commercial farms would find it cost effective to attain the same yields as in research experiments.

CEA allows farmers to produce over an extended season or year-round in a variety of environments. For instance, Kowalczyk et al. (2020) carried out an experiment to estimate the yield of hydroponic cucumber plants for 17 weeks in winter by controlling three variants of supplementary lighting. Although there were yield gaps among the types of light combinations, the experiment showed that all estimated yields were higher than the average yield of cucumbers grown “under protection” (another term for CEA) based on data from the 2019 CHS (table 2).

These supplementary lighting systems contributed to a higher concentration of nutrient uptake of cucumbers, and the experiment led to higher and more stable yields during winter cultivation. The extended season or year-round production alone increases production potential considerably. Extended production seasons and maximizing grow space in vertical systems combine to greatly enhance yields per unit of horizontal growing space. For example, Touliatos et al. (2016) showed that the yield of lettuce per unit of occupied growing floor area can be about 14 times higher in vertical hydroponic systems than in horizontal hydroponic systems, when planting density is 20 times higher. Hence, vertical growing systems are likely to yield less produced output per plant.

Fully controlled environments are entirely closed, meaning that all inputs—including light in the form of artificial sunlight—are provided by the system. These systems also offer the potential for much more efficient use of water and agricultural chemicals but likely require greater energy use. These cutting-edge technological systems are relatively new to the market in the United States, but given their potential for producing nutritious food in communities that are not well-suited for traditional outdoor agriculture, investment in them is expanding.

Table 2

Estimated yields from USDA, National Agricultural Statistics Service (NASS) and scientific experiments in conventional, protected, and hydroponic systems

<table>
<tr><th rowspan="3"></th><th colspan="2">Estimated yields from USDA, NASS data (kg/m²)</th><th colspan="4">Estimated yields from scientific experiments</th></tr>
<tr><th rowspan="2">Conventional, open-field production</th><th rowspan="2">Under protection</th><th rowspan="2">Conventional (kg/plant)</th><th colspan="2">Hydroponics</th><th rowspan="2">Source</th></tr>
<tr><th>(kg/plant)</th><th>(kg/m²)</th></tr>
<tr><td>Cucumbers</td><td>1.8</td><td>39.3</td><td>–</td><td>–</td><td>42.8–58.9</td><td>Kowalczyk et al. (2020)</td></tr>
<tr><td>Lettuces, head</td><td>3.8</td><td rowspan="3">48.7</td><td>–</td><td>–</td><td>–</td><td></td></tr>
<tr><td>Lettuces, leaf</td><td>2.3</td><td>–</td><td>–</td><td>–</td><td></td></tr>
<tr><td>Lettuces, romaine</td><td>3.3</td><td>1.1</td><td>1.64 (DWC)
1.32 (NFT)</td><td>74</td><td>Touliatos et al. (2016), Majid et al. (2021)</td></tr>
<tr><td>Peppers, bell</td><td>3.6</td><td rowspan="2">21.8</td><td>–</td><td>–</td><td>–</td><td></td></tr>
<tr><td>Peppers, chile</td><td>1.8</td><td>0.53</td><td>2.9</td><td>–</td><td>Bione et al. (2021)</td></tr>
<tr><td>Tomatoes</td><td>9.6</td><td>38.7</td><td>–</td><td>–</td><td>48</td><td>Delaide et al. (2019)</td></tr>
<tr><td>Strawberries</td><td>6.1</td><td>8.7</td><td>0.4</td><td>1.4</td><td>–</td><td>Talukder et al. (2018)</td></tr>
</table>

DWC = deep water culture. NFT = nutrient film technique. 1 kg = 2.2 pounds. kg = kilogram. m = meter. 1 m = 3.28 feet.

Note: Estimated yields from USDA, NASS data were calculated by the authors based on the 2021 Vegetables Annual Summary for conventional, open-field production and the 2019 Census of Horticultural Specialties (CHS) for crops grown under protection. The CHS yield data do not differentiate between varieties of lettuce or peppers grown under protection. – indicates that data are unavailable for a given row and column. A yield of lettuce from hydroponic systems is approximately 1.5 kilograms/3.3 pounds per plant (Majied et al., 2021), and about 50 lettuce plants can be planted per square meter (Touliatos et al., 2016).

Source: USDA, Economic Research Service calculations using USDA, National Agricultural Statistics Service data.

Although established research has shown yield and production gains through the use of CEA systems, future growth of more advanced systems is faced with various challenges as well as opportunities. Some of the most commonly cited opportunities and challenges include issues surrounding environmental impact and supply chain viability, capital intensity and operating costs, and consumer perception.

Supply Chain Viability and Environmental Effect

Indoor agriculture allows for production in areas where climate or soil conditions are unsuitable for traditional outdoor agriculture (USDA, Agricultural Marketing Service (AMS), 2022). Locating indoor farms close to cities based on consumer demand could help diversify the supply chain and reduce reliance on crops grown elsewhere. Locally grown crops could also help to increase food availability during disruptions due to weather, infrastructure failures, or logistics bottlenecks (Pinstrup-Anderson, 2018). For example, CEA farms located close to the communities the farms serve have the potential to help reduce these types of disruptions and strengthen the U.S. food supply chain.

When vegetables and other food crops are produced in CEA systems near cities, there may be some reduction in the transportation carbon footprint associated with those crops (Stein, 2021; Sheng, 2018), although there is conflicting evidence on this issue (Oosterwyk, 2022). Researchers note that CEA facilities close to their markets will reduce the transit time from harvest to the consumer (Beachum et al., 2019). Fresher produce can also increase the nutritional value of fruits and vegetables (Barrett, 2007).

Indoor agriculture can produce a higher volume of a few specialty crops by using water conservation methods, limiting the effect of water scarcity on its production. By some estimates, the crops can consume 80–99 percent less water than traditional agriculture due to recycling gray water, precision irrigation, and lowering evaporation (Al-Kodmany, 2018; Pinstrup-Anderson, 2018; Shamshiri et al., 2018). However, the relative water footprint of hydroponic systems compared with traditional agriculture is unknown because hydroponic systems may use water for heating, cooling, and other purposes (Gómez et al., 2019). The number of crops being grown commercially in more advanced hydroponic CEA operations is also still quite limited.

The acres per unit of production for CEA are less than traditional arable land, particularly for vertical agriculture systems (Sheng, 2018). For example, some vertical farm companies claim it would take a conventional farm 390 acres to produce what a vertical farm can on 1 acre (Severson, 2021). In addition, since vertical farm crops are grown in enclosed environments, crops are generally grown without pesticides, and there is often a reduction in the use of other chemicals, herbicides, and fertilizers that could have adverse environmental effects (Pinstrup-Anderson, 2018; Shamshiri et al., 2018; Zhang et al., 2020).

Capital Intensity and Other Operating Costs

High startup and operational costs are among the significant challenges facing the growth of indoor agriculture with highly automated systems. For example, the startup costs for a vertical farm can range from $150 to $400 per square foot compared to $50 to $150 per square foot for a greenhouse (Stein, 2021). The challenges of running a vertical farm also include the consistency in watering between the top and bottom of systems, lack of consistency in lighting from top to bottom, and labor associated with harvesting at different heights (Sheng, 2018).

Labor costs in CEA systems, for example, are higher than those associated with the conventional production of fruits and vegetables since advanced CEA systems require technical and scientific expertise (Souza et al., 2021; Agrilyst, 2017; Hadley, 2017). However, while labor costs are higher, advanced CEA farms have the potential to create new job opportunities in cities and areas immediately surrounding urban areas for skilled scientists and high-tech positions such as biologists, engineers, software developers, data scientists, and horticulturists (Al-Kodmany, 2018; Kalantari et al., 2017; Shamshiri et al., 2018). Some research suggests that robotics and automation have the potential to help bring operational labor costs down, but they are costly to fully integrate into the vertical farming system and the systems have limitations (Shamshiri et al., 2018; van Delden et al., 2021).

In addition, the primary concern of indoor farms is the energy cost, specifically the lighting needed to grow the crops (Stein, 2021). For instance, Agrilyst (2017) estimated that energy costs average around $3.45 per square foot for a small farm and $8.02 per square foot for a large farm (>10,000 square feet) for a 16-hour photoperiod. The extensive energy use by advanced CEA systems makes the systems more sensitive to energy price fluctuations. LED lights are an example of a technological advance that lowered costs for CEA systems. More expensive initially than traditional lighting systems, these lights use less energy and last much longer (Mills & Dunn, 2017).

Although LED lighting has significantly improved efficiency for agricultural applications, research shows that even at maximum efficiency, producing many vegetable and staple crops will not be economically viable (Patterson et al., 2018). Current energy technology may need to be more efficient to grow lower value food crops competitively. One study noted that, under certain assumptions about the price of energy and the price of wheat, the cost of energy to produce 1 unit of wheat would be 100 times the price of that unit (Bugbee, 2015). This study looked at the energy cost and none of the additional overhead associated with fully enclosed vertical farming. The data provide preliminary evidence and theoretical support for the argument that advanced CEA, which relies on artificial lighting, can only scale up with significant advancements in energy technology to make it economically feasible to grow lower value energy-intensive crops. CEA farms that require extensive energy to operate could potentially offset some of the higher energy costs by adopting renewable energy infrastructure (Beachum et al., 2019).

Consumer Perception

While some CEA producers brand and label their products as having specific attributes that can earn a premium (including organic), it remains controversial if "soilless" crops should be allowed to be certified organic. The European Commission ruled that soilless-grown crops cannot be certified organic in the European Union, but the certification has been ruled acceptable in the United States (see appendix C, "The Organic Designation of Hydroponic and Aquaponic Crops").

There is evidence that consumers overall have a positive perception of the vertical farming industry (Ares et al., 2021). The study suggests that the main driver of a positive attitude by consumers of the vertical farm sector was the perceived sustainability the sector offers. In addition, some consumers may perceive that producing crops close to the point of consumption leads to greater freshness, flavor, and possibly nutritional content (Nie & Zepeda, 2011). There may also be differences in perceived taste quality between vegetables and fruits grown in soil compared with those grown in soilless media (hydroponics) (Coyle & Ellison, 2017).

Agrivoltaics: Colocation of Solar Panels and Agricultural Production Systems

Agrivoltaics (AV) is the colocation of a crop, pasture, or environmentally beneficial vegetative cover with solar panels. In AV systems, land is used for solar panels, which generate renewable electricity primarily either for on-site use or for the electricity grid. The same land is also used to grow beneficial vegetation underneath the solar panels, such as native grasses and wildflowers that serve as habitat for pollinators and/or is used for livestock grazing or crop production (e.g., specialty crop production).

Traditionally, the term agrivoltaics referred to one of three types of systems: growing crops between solar panels, placing solar photovoltaic (PV) modules on the roof of greenhouses (a combination of CEA and agrivoltaics), or growing crops beneath raised solar panels (Sekiyama & Nagashima, 2019). Agrivoltaics is a new technological system, however, and as such, the definition remains malleable. The term has been applied to a wide range of systems, including the colocation of crop production in greenhouses or open fields, livestock grazing, or pollinator habitat with a wide range of solar system configurations.

Agrivoltaics: Investments in Research and Development

As of 2021, the U.S. AV sector was in an early phase of development. Research projects to examine the feasibility of various AV systems were being funded by the U.S. Department of Energy, Office of Energy Efficiency & Renewable Energy, Solar Energy Technologies Office (DOE-SETO) and the USDA, National Institute of Food and Agriculture (NIFA), among others. DOE-SETO has been funding research on agrivoltaics since 2015, and funding has expanded significantly since then. In fiscal year 2020, DOE-SETO provided $130 million in funding for solar projects, and $7 million of that funded four AV projects (Davis & Macknick, 2022; DOE-SETO, 2020). Table 3 presents a list of AV projects funded by the DOE through June 2021 (DOE-SETO, 2021).[21]

[21] Additional projects have been funded by DOE since 2021, in particular, the InSPIRE 3 funding program began on January 1, 2022 (Macknick et al., May 15, 2022). All funding amounts are in nominal dollars.

In 2021, USDA, NIFA provided $10 million in funding for an interdisciplinary project to evaluate solar installation design across a diverse set of crops using a combination of field research, biophysical and economic modeling, and farmer surveys. The goal of this research is to evaluate the performance of a wide array of AV systems and provide information on the agricultural and economic feasibility of the systems by region (USDA, NIFA, 2021). In 2022, the USDA expanded its support of AV through its Partnerships for the Climate-Smart Commodities Project. Specifically, USDA provided $2.3 million in funding for university partners who will conduct research on the benefits of AV for greenhouse gas reduction and will provide technical and financial support for a historically underserved community, Hispanic farmers and ranchers in Texas (USDA, 2022a).

Table 3

Agrivoltaics projects funded by the U.S. Department of Energy, Solar Energy Technologies Office (DOE-SETO) through June 2021

DOE-SETO-funded agrivoltaics projects	Funding/Awardee	Award start date	Brief project description
Impacts of Dual-Use Solar on Crop Productivity and the Agricultural Economy in Massachusetts and Beyond	$1,819,996 - University of Massachusetts Amherst	11/12/2020	Install solar panels over existing commercial crop production
The Agri-Solar Clearinghouse	$1,592,481 - National Center for Appropriate Technology	11/12/2020	Establish a database of agrivoltaics research and connecting people participating in agrivoltaics
Luminescent Enhancement for Combined Solar and Commercial Agriculture	$199, 834 - Soliculture	01/01/2019	Develop a new solar mounting system for greenhouses using technology tailored to crops grown
InSPIRE 2.0: Facilitating Low-Impact Solar Development through Data and Analysis for Environmental Resiliency and Compatibility	$1,889,928.00 - NREL	10/01/2018	Examine effects of solar installations on revenue and production on agricultural land; conduct studies on land management practices at solar facilities currently, the costs of alternative practices, and evaluation of potential environmental benefits
Meeting SunShot Cost and Deployment Targets through Innovative Site Preparation and Impact Reductions on the Environment (InSPIRE)	$968,523 - NREL	10/01/2015	Assess existing solar siting practices and evaluation of alternative methods that reduce environmental and land use effects, including through agrivoltaics
Pole-based Solar Mounting and Tracking System for Use in Cattle Production	$200,000 - FarmAfield Labs	7/1/2019	Develop a solar mounting and tracking system for cattle feeders
Integrated Photovoltaic (PV) System Design and Management Platform for the Cooptimization of Regenerative Cattle Grazing and Photovoltaics Solar Generation	$1,771,161 - Silicon Ranch Corporation	11/12/2020	Test and analyze a new design for a solar panel tracking and control system to allow for colocation of solar panels with pasture grazed cattle
Evaluation of Economic, Ecological, and Performance Impacts of Co-Located Pollinator Plantings at Large-Scale Solar Installations	$1,820,000 - University of Illinois at Chicago	11/12/2020	Research the environmental, solar panel performance, and cost effects of pollinator habitat at 5 large solar installations, 10 megawatt or larger, in the Midwest and Mid-Atlantic regions
The Energizer Bunny: Dual-Use Photovoltaic and Pasture-Raised Rabbit Farms	$182,500 - Michigan Technological Institute	02/01/2020	Evaluate the effects of the colocation of rabbit farms with a solar installation, including potential benefits to rabbit production from shade and protection from aerial predators

Note: Projects funded on November 20, 2020, are included in the $7 million of funding referenced above. NREL = U.S. Department of Energy's National Renewable Energy Laboratory.

Source: USDA, Economic Research Service using information from U.S. Department of Energy, Solar Energy Technologies Office, 2021.

Agrivoltaics Sector: Motivations for Development and Expansion

Prior to 2016, most of the growth in renewable electricity capacity in the United States was from utility-scale wind development in rural areas.[22] Subsequently, increases in utility-scale solar capacity exceeded wind capacity additions. Beginning in 2012, solar generation began a dramatic rise. Solar generation more than doubled in 2012 and 2013, and the annual average growth rate was 41 percent between 2015 and 2020 (EIA, 2021b). Despite its growth, solar generation was just 3 percent of total U.S. electricity generation in 2020 but is projected to be 20 percent of total generation by 2050 (EIA, 2021c).[23] Policies to address climate change, such as the Inflation Reduction Act of 2022, led to expanded funding for solar and wind development and are expected to dramatically increase the pace of development (Gagnon et al., 2022).

A major driver to develop AV systems was to mitigate concerns over land use competition that was limiting the expansion of utility-scale solar capacity (Davis & Macknick, 2022; Bayly, 2021; Pascaris et al., 2021; Sekiyama & Nagashima, 2019; Weselek et al., 2019; Sacchelli et al., 2016). These concerns are particularly salient in rural areas, where, as of 2020, 74 percent of utility-scale solar development was located and concerns over the effects of large-scale solar have led to local zoning restrictions in some States (NREL, 2022b).[24] Although the cumulative amount of land used for solar development is projected to remain small relative to the total amount of farmland, in a traditional utility-scale solar development the land is cleared prior to development and the previous land use is replaced with solar panels (DOE-EERE, 2021; Horowitz et al., 2020). Further, much of the same land that is ideal for large-scale commodity crop production is also ideal for large-scale solar installations (Adeh et al., 2019).

Advocates argue that agrivoltaics could reduce the land use conflicts in rural areas and provide other local agri-environmental benefits, including improving crop productivity and providing pollinator habitat while improving the performance of the solar panels (DOE-SETO, 2022; Andrew et al., 2021; Dolezal et al., 2021; Barron-Gafford et al., 2019; Dinesh & Pearce, 2016). Additionally, utility-scale AV solar installations provide revenue to landowners from energy leases (DOE-SETO, 2022; Barron-Gafford et al., 2019; Sekiyama & Nagashima, 2019; Ravi et al., 2016). Whether AV systems can achieve these beneficial outcomes is unclear. In the face of increasing adverse effects from climate change, however, AV systems provide an additional path for expanding renewable electricity capacity.

Agrivoltaics: Research and Development

There has been an increase in research, both internationally and in the United States over the last 5 years, on the agricultural and economic feasibility of AV systems (Davis & Macknick, 2022; Graham et al., 2021; Sharpe et al., 2021; Maia et al., 2020; Schindele et al., 2020; Barron-Gafford et al., 2019; Majumdar & Pasqualetti, 2018; Marrou et al., 2013). The systems being researched vary along a wide range of characteristics, including the type and configuration of solar panels and installations; the type of vegetative cover, pollinator-friendly plants, crops, and/or livestock production that is co-located; and whether the system is a distributed generation system, similar to rooftop solar panels, that is designed to provide electricity primarily for on-site use or a large-scale system designed to provide electricity to the grid for off-site use.

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[22] Utility-scale systems are large-scale, commercial systems or power plants with greater than 1 megawatt of capacity; typically, these systems are connected to the electricity grid and provide electricity primarily for offsite use (EIA, 2022a).

[23] This projection includes only utility-scale solar. The projection does not include rooftop solar or electricity that is generated for use in a distributed system (i.e., for use primarily onsite).

[24] The share of solar-generated electricity in rural areas was calculated using the U.S. Department of Commerce, Bureau of the Census 2019 TIGER/Line Shapefiles, overlayed with data on the location of solar generators through 2020 from the U.S. Department of Energy, Energy Information Association (U.S. Department of Commerce, Bureau of the Census, 2019; EIA, 2021a).

Researchers have found mixed results when evaluating the effects of AV systems on environmental conditions at sites with solar PV co-located with pollinator-friendly or native vegetative cover (Graham et al., 2021; Walston et al., 2021; Choi et al., 2020; Adeh et al., 2018). For example, Walston et al. (2021) found that planting native grasses beneath solar panels increases pollinators, water retention, and carbon storage as compared to a traditional bare soil solar installation. Adeh et al. (2018) also found increases in soil moisture beneath solar panels. Additionally, they found increases in late-season biomass, specifically pasture grass cover. Graham et al. (2021) found increases in floral abundance but delayed bloom timing on plots that were partially shaded by solar panels. The partially shaded plots did not reduce pollinator abundance as compared to full sun areas, but there were declines in fully shaded plots. Pollinator flower visitation rates were consistent, independent of shading, suggesting that pollinators used habitats beneath solar panels.

Conversely, Choi et al. (2020) found that soil carbon and nitrogen were lower and that the distribution of soil moisture was affected. Specifically, precipitation accumulated beneath the edges of the panels and was reduced under the panels. Further, a study of an AV system with sheep grazing found that shade from solar panels reduced the amount of pasture grass, although they posit that pasture quality was higher as compared to pastures without solar panels (Andrew et al., 2021).

Additional research evaluated the effects of AV systems on crop production (Barron-Gafford et al., 2018; Sekiyama & Nagashima, 2019). Barron-Gafford et al. (2019) evaluated the effects of an AV system on three specialty crops—chiltepin pepper, jalapeno, and cherry tomatoes. They found that soil moisture increased, and water demand was reduced under the PV installation. Further, they found that temperatures under the panels were cooler during the day due to the shade provided by the panels and warmer at night. In addition to the agri-environmental effects of the panels, they found that the vegetative cover under the panels could improve panel performance. The temperature of the panels was reduced, likely due to plant transpiration, which could lead to an increase in solar generation during the growing season.

Sekiyama & Nagashima (2019) conducted research on sweet corn grown in an AV system. They found that the configuration of the solar installation, specifically the distance between the panels, was a key factor in corn yields. A low-density AV system increased sweet corn yield, but a high-density system decreased yield. This finding is not unexpected because corn is a shade-intolerant crop. Additionally, in this experiment, the panels were not elevated to allow for machinery to be used in farming, so the applicability of the results to commercial-scale corn production could not be established (Sekiyama & Nagashima, 2019). To date, AV systems with commodity crop (e.g., wheat, corn, soybeans) production have been infeasible, although research is ongoing.

Existing research has largely focused on the feasibility of agricultural production or the microclimate effects of AV systems and not whether the systems are commercially viable crop production systems. Schindele et al. (2020) examined the costs associated with the production of a specialty crop (potatoes) and a commodity crop (winter wheat). They estimated that due to the premium price paid for organic potatoes, the crops could be profitably grown in an AV system, but conventional potato production was not profitable. They concluded that AV systems are suitable for specialty crops (such as berries, fruits, and wine grapes) and particularly for organic specialty crops because of the price premium.

Additionally, they estimated that the costs for winter wheat production would be higher in an AV system, such that it was also not profitable. Two factors led to higher costs in winter wheat: Winter wheat does not tolerate shade, and the solar panels had to be raised to allow for machinery to operate underneath the panels (Schindele et al., 2020). In general, for large-scale commodity crop production, panels must be spaced and raised to accommodate machinery, which increases the costs for the system and lowers the number of solar panels in a given area, reducing the generation capacity of the AV system (Schindele et al., 2020).

Horowitz et al. (2020) modeled scenarios for three AV configurations and a typical solar PV installation. They found that all evaluated AV systems had higher average costs than a traditional solar PV installation. The lowest costs were associated with AV systems with grazing or pollinator habitat, while AV crop systems had the highest costs (Horowitz et al., 2020). The findings are consistent with the share of AV systems that have been implemented in the United States today. The most prominent systems are those with pollinator habitat, and the least common include specialty crops.[25] [26] The agricultural feasibility for some specialty crops has been established, but the industry is in its early stages, and the economic feasibility of specialty crop production in an AV system is not well established (Bowman et al., 2022; Schindele et al., 2020). Research is underway that will provide needed information on the technical feasibility and commercial viability of agricultural production in different types of AV systems (Davis & Macknick, 2022). Unlike CEA, particularly traditional greenhouse CEA, commercial specialty crop production with AV systems is much more limited.

Agrivoltaics: Commercial Sites

Jack's Solar Garden is an example of an AV production system, a community solar project in Boulder County, Colorado. As of 2021, the site had approximately 3,200 solar panels on 5 acres with a generating capacity of 1.2 megawatts (MWs), enough to supply electricity to 200–300 homes annually.[27] [28] [29] In addition, Jack's Solar Garden is partnering with the U.S. Department of Energy's National Renewable Energy Laboratory (NREL) and local government agencies, universities, and nonprofits that have established vegetative cover underneath the solar panels. This vegetation includes pollinator-friendly plants, specialty crops, and pasture for grazing. Research is being conducted at these sites to evaluate the effects of solar installations on agricultural production and environmental outcomes (Davis & Macknick, 2022; NREL, 2021). Jack's is unique because the site includes crop production, pollinator habitats, and pasture grasses located with solar panels on one site.

As of 2022, the predominant AV system that had been implemented was a utility-scale solar installation planted with pollinator-friendly vegetation, approximately 274 out of 304 AV installations. Of these, there were approximately 15 AV sites with pollinator-friendly vegetation and sheep grazing (NREL, 2022a).[30] Some examples are the utility-scale solar projects with pollinator-friendly habitats that are operated by Enel Green Power in Minnesota (Bjorhus, 2021). The utility uses sheep to manage and fertilize the native and pollinator-friendly vegetation at some of its 16 utility-scale solar installations (Bjorhus, 2021). Also in Minnesota, Xcel Energy was planning a large, 480-megawatt solar project that would include pollinator-friendly vegetation

[25] As of October 6, 2022, the NREL InSPIRE Agrivoltaics site map included 304 AV sites. Of these, 259 were AV sites with pollinator habitats planted beneath the solar panels. An additional 15 included pollinator habitat and grazing, 9 included crop production, and 1 was in a greenhouse (NREL, 2022a). The map is a "dynamic map" and may not include locations for all AV sites. It is regularly updated with new information.

[26] Of note, the data used to estimate costs were limited. The data were collected from interviews with 10 solar PV and installation companies and with construction cost guides, 7 of the companies being in the United States (Horowitz et al., 2020).

[27] According to NREL, as of June 2020, Jack's was one of more than 1,200 community solar projects in the United States (Heeter & Chan, 2020). Other community solar installations are not generally AV sites; the installations provide their customers an opportunity to purchase solar-generated electricity (U.S. Department of Energy, Office of Energy Efficiency & Renewable Energy, n.d.).

[28] For more information, search for Jack's Solar Garden on the internet.

[29] The U.S. Department of Energy, Energy Information Administration's measure of average annual electricity consumption by a residential utility customer in 2020 was 10,715 kilowatts, and the capacity factor for utility-scale solar photovoltaic (PV) in 2020 was 24.2 percent (EIA, 2022b). Using these data, the authors estimated that the number of households supplied is 237, but there is variation in capacity factor by region and solar installation and variation in household energy demand.

[30] Of the projects listed on the NREL InSPIRE Agrivoltaics Map as of October 6, 2022, 274 of the 304 AV sites included pollinator-friendly habitats, and 35 included sheep grazing (NREL, 2022a). The map is a "dynamic map" and may not include locations for all AV sites. It is regularly updated with new information.

(Davis & Macknick, 2022). As of 2022, 84 percent of the AV sites with pollinator-friendly vegetation were located in the Midwest, with 52 percent in Minnesota, but there were sites in many States (NREL, 2022a).

Generally, the contribution of pollinators from AV sites to crop production and the value of AV pollinator habitat to crop production is not well-established (Dolezal et al., 2021). The contribution depends on several factors, including the proximity of the habitat to crops, land management practices, and the pollinator dependence of the crops (Kleijn et al., 2015; Zurbuchen et al., 2010). Further, the ground is typically cleared before the installation of the solar panels. After installation, the area beneath and between the panels is planted with a pollinator-friendly habitat (Horowitz et al., 2020). If the site was established on previously productive agricultural land, an evaluation of the net effect of the pollinator habitat on agricultural production would need to consider prior production.

There are only a few AV sites that include crops, generally specialty crops, and in many cases, the crops are grown in part or entirely for research purposes (Davis & Macknick, 2022).[31] [32] As of 2022, a 12-acre wild blueberry farm in Rockport, Maine, was the largest AV system with crop production. Beginning in 2021, Blue Wave Solar began the installation of 10,608 solar panels over an existing blueberry farm with low-bush blueberry fields. The first of its kind in Maine, the project will provide information on the technical feasibility of farming blueberries in an AV system and whether an AV system with blueberry production is commercially viable (Davis & Macknick, 2022). Of particular interest is whether the costs to install the panels at an increased height of 8 to 10 feet to allow for harvesting will prove to be cost effective over the long run (Turkel, 2021).

While AV sites with pollinator-friendly habitats have been developed with utility-scale solar installations, AV systems with specialty crop production (including Jack's Solar Farm (1.2 megawatts) and the Maine blueberry farm (4.2 megawatts)) are generally smaller in scale than traditional utility-scale solar development. For comparison, as of 2021, there were 984 utility-scale solar installations in the United States that were 5 megawatts or greater, and the median size was 20 megawatts (Berkeley Lab, 2021). Although consumers have been willing to pay a premium for electricity from renewable energy (including solar), it is not well-established if consumers will pay a premium for solar-generated electricity because the electricity was generated at an AV site.

AV sites are commonly incentivized by State and local programs because of the sites' potential to provide local agri-environmental benefits and mitigate concerns regarding land use competition (Davis & Macknick, 2022; Groom, 2022; Ingram, 2022; Bayly, 2021; Bryce, 2021). For example, State agencies in Minnesota encourage AV systems with native grasses or pollinator habitats at large-scale solar sites (Bjorhus, 2021). In Massachusetts, AV systems can qualify for an incentive payment through the Solar Massachusetts Renewable Target (SMART) Program that began in 2018 (Sylvia, 2020). Federal and State programs, including research funding to expand renewable energy to address climate change, along with local restrictions on utility-scale solar development, provide incentives for continued expansion of AV systems.

Agrivoltaics: Prospects

As the demand for renewable energy increases, AV systems provide an opportunity to expand renewable capacity while providing local agri-environmental benefits. AV systems include a wide range of solar installa-

[31] As of October 6, 2022, the NREL InSPIRE Agrivoltaics site map included 9 crop production sites out of 304 total—4 were active research sites, and 7 were used for ongoing research (NREL, 2022a). The map is a "dynamic map" and may not include locations for all AV sites. It is regularly updated with new information.

[32] As of March 2022, Jack's was one of seven AV sites where DOE SETO was funding research on crop production and one of nine AV sites where DOE SETO was funding ecosystem research, specifically on pollinator-friendly vegetation (Macknick, Jordan. Email March 10, 2022).

tions, from on-farm systems to large-scale systems designed to supply electricity to the grid. The cost of these systems varies greatly, and the future of agrivoltaics remains unclear. With few exceptions, the commercial systems in the United States are utility-scale solar installations that have been planted with native or pollinator-friendly vegetation and, in some cases, include sheep grazing. While pollination supports a significant portion of crop production, the contribution of pollinators associated with AV pollinator habitats to proximate crop production has not been well-established, though research is ongoing.

The AV sites with crop production largely include those sites with a variety of specialty crops that can be harvested by hand. In these systems, researchers have found benefits for shade-tolerant crops, particularly in arid regions, due to the benefits of increased soil moisture beneath the panels and the cooling effect of the plants on the solar panels. Because the industry is so new, the commercial viability of AV systems with crop production is yet to be established. Recent and ongoing research will provide critical information on the agricultural and economic feasibility of AV crop systems in the United States.

Conclusion

This report provides a broad examination of two technological systems that are incorporating novel approaches for agricultural production. Although controlled environment agriculture (CEA) has a long tradition in greenhouse production, new innovations including hydroponics and entirely enclosed systems are pushing the boundaries of how and where specialty crop production occurs. Agrivoltaics (AV), while currently implemented largely with native and pollinator-friendly habitats, may provide opportunities for crop or livestock production beneath and alongside solar panels. There are benefits to each of these systems, but the findings in this paper suggest that these systems, to varying degrees, face technical and economic challenges.

Through analysis of data on CEA production, the paper finds that the market for CEA crops has experienced unsteady growth from 1998 to 2019. Still, the value of production for crops produced in CEA systems in the United States has increased from $296 million in 1998 to more than $626 million (in constant dollar terms) between 1998 and 2019. The number of CEA operations almost tripled to 2,994 during the same time span. Approximately 60 to 70 percent of the crops grown in CEA systems are tomatoes, lettuce, and cucumbers, with hydroponic systems being the predominant method of cultivation. Investments in indoor farming have grown, but the future is uncertain as more is learned about the commercial viability of specific production systems. Nevertheless, the surge in reported planned CEA investments since the last Census of Horticultural Specialties (CHS) in 2019 indicates a likely increase in area and production for CEA-grown food crops. The next CHS is expected to be published in December 2025, featuring calendar year production, area, and sales for CEA-grown food crop data from calendar year 2024.[33] The upcoming CHS will provide an updated snapshot and determine whether the many reports of new investments have been realized and reflected in significantly enhanced CEA production and sales for food crops.

As of 2021, the AV industry in the United States was in its initial stage of commercial expansion. The majority of AV sites that provided solar generation to offsite customers were utility-scale solar developments planted with native and/or pollinator-friendly vegetation. Research projects were underway—funded by DOE-SETO, USDA, NIFA, and others—to examine the technical and economic feasibility of different

[33] The Census of Horticultural Specialties publication is anticipated to be available in December 2025 with calendar year 2024 results based on the reference years and the timing of the last two publications. USDA, NASS is expected to release the 2022 Census of Agriculture publication in the spring or summer of 2024. This comprehensive report will provide a broad overview of the entire agriculture sector based on the surveys conducted in 2022.

types of AV systems. These types of systems include those with native and/or pollinator-friendly vegetation, specialty and commodity crop production, and livestock grazing with a variety of solar configurations. Funding has expanded significantly since DOE-SETO provided initial support for the industry in 2015, including $7 million from DOE-SETO in fiscal year 2020 and $10 million from USDA, NIFA in 2021.

Among the numerous challenges to CEA systems are high construction costs, increasing competition from other countries exporting CEA produce to the United States, high and potentially volatile input costs for items such as labor and energy, and the consumer perception of specialty crops that might need to be sold at a premium relative to conventional field grown crops. Nevertheless, it appears that indoor agricultural production systems are becoming more widespread, more sophisticated, and, in some cases, more commercially feasible (but only for a limited number of crops and production systems). The crops produced from these systems include primarily tomatoes, cucumbers, leafy greens, microgreens, and some berries. It is difficult to get more than anecdotal information on the existence and potential for controlled environment agriculture systems for relatively lower value field crops such as wheat or other row crops. AV systems have been established with pollinator friendly vegetation, livestock grazing, and specialty crop production. Research examining the agricultural and economically feasibility of various types of AV systems is ongoing.

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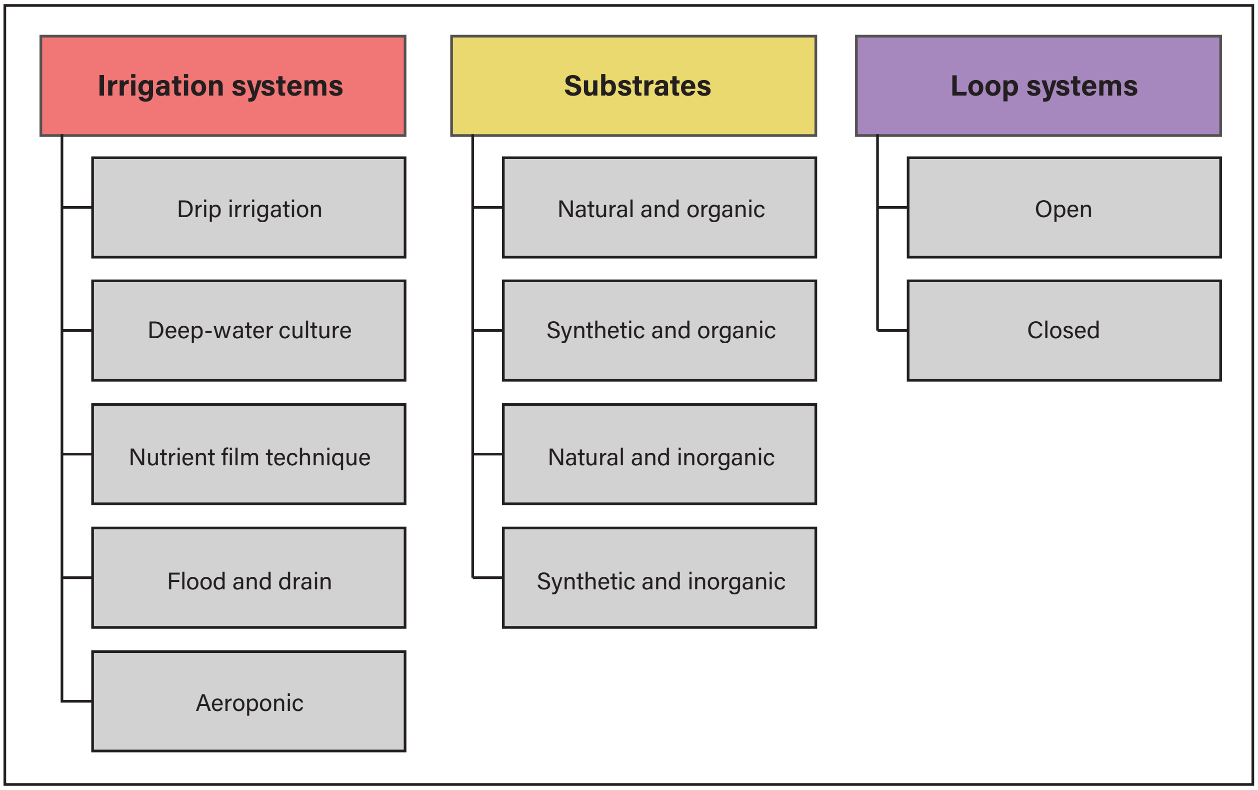
Appendix A: The Design and Operation of Hydroponic Systems

Figure A.1
Types of controlled environment agriculture hydroponic systems



Note: Hydroponic systems can be classified in various ways, such as the types of irrigation system and substrate (growing media) used and whether the systems are open- or closed-loop systems (figure A.1).

Source: USDA, Economic Research Service using data from Eldridge et al. (2020), Pignat et al. (2017), Maucieri et al. (2019).

Types of Irrigation Systems

Hydroponic systems include drip irrigation, deep-water culture, nutrient film technique, flood and drain (also called ebb and flow), high-pressure atomization, and aero-hydro systems.

- Drip irrigation systems (DIS) – A nutrient solution is conveyed through small pipes or tubes and drips onto an inert substrate to provide moisture and nutrition to plants (Eldridge et al., 2020).[34] Drip irrigation allows only the area immediately around individual plants' roots to become wet (Geilfus, 2019) and is only applied periodically (Maucieri et al., 2019). These systems are particularly suitable for fruiting crops like tomatoes, cucumbers, peppers, and strawberries (Gómez et al., 2019).

- Deep-water culture (DWC) – A substrate is not used in these systems. Instead, the plant roots are continuously suspended in an oxygenated nutrient solution, with plants supported by a membrane that holds the upper parts of the plants above the water (Eldridge et al., 2020; Butcher et al., 2017; Schröder & Lieth, 2002). DWC systems work particularly well for leafy greens and herbs (Gómez et al., 2019). DWC may also be called deep-flow technique, raft, raceway, or floating hydroponics (Gómez et al.,

[34] Substrates are porous materials that hold the roots of the plants and allow oxygen and the nutrient solution to be slowly absorbed by plants' roots over time.

2019). According to Schröder & Lieth (2002), DWC systems are generally known as "hydroponic systems."

- Nutrient film technique (NFT) – Plants are grown on sloped troughs, with the upper part of the plants supported by growing media (Eldridge et al., 2020). The bottoms of the plants' roots are exposed to a thin layer (or film) of recirculating nutrient solution (Domingues et al., 2012; Eldridge et al., 2020). The upper portion of plants' roots dangle in the air (Eldridge et al., 2020). Like DWC, NFT systems are well-suited for leafy greens and herbs (Gómez et al., 2019).

- Flood and drain systems (FDS) – Also called ebb and flow systems, seedlings are planted in a growing medium and nutrient solution that periodically floods and completely submerges the medium (Geilfus, 2019). The solution is then drained from the medium and recirculated through a pump to flood the medium again (Geilfus, 2019).

In aeroponic systems—in contrast to the irrigation systems described above—plant roots are exposed to aerosol droplets that contain nutrients (Eldridge et al., 2020). These aerosols may be applied continuously or intermittently (Lakhiar et al., 2018). There are various methods for generating aerosols and applying the aerosols to the roots of plants.

Types of Substrates

Another defining characteristic of hydroponic systems is the type of substrate used. Substrates are also referred to as growing media, potting media, or soilless media (Burnett et al., 2016). Substrates can be categorized as natural or synthetic and organic or inorganic (Pignata et al., 2017). Organic substrates—which are permitted under USDA's National Organic Program—include rockwool, peat, coconut coir (i.e., fiber), compost, anaerobic dairy manure digestate, rice hulls, bark, and wood chips or sawdust (Burnett et al., 2016). Inorganic substrates contain natural materials such as sand and mineral products such as perlite and vermiculite, which are derived from industrial processes (Maucieri et al., 2019). Some of these inorganic substrates may also be allowed under the National Organic Program (Burnett et al., 2016).

Open-Loop and Closed-Loop Systems

In open-loop systems (also called run-to-waste systems), the nutrient solution is not recycled. In closed-loop, or recirculation, systems, the nutrient solution is replenished with nutrients and then reused. Maucieri et al. (2019) reviewed several advantages and disadvantages of closed systems compared with open systems. The advantages of closed systems are less waste, less water pollution, and a more efficient use of water and fertilizer (nutrients). The disadvantages of closed systems are that the water used must be of higher quality, requiring higher investments, because the nutrient solution may accumulate greater concentrations of pathogens.

Opportunities and Challenges of Hydroponic Systems

For many crops, hydroponic systems improve yields and quality compared to traditional agricultural systems (Gómez et al., 2019; Touliatos et al., 2016; Majid et al., 2021). This improvement is achieved through precise control of inputs (such as water and nutrients) and a reduction in pests and pathogens, with less use of some chemicals compared to conventional outdoor production systems (Majid et al., 2021; Somerville et al., 2014; Gómez et al., 2019; Benke & Tomkins, 2017). Yields are also enhanced by the optimal use of temperature and lighting, improving photosynthesis (Walters et al., 2020). Hydroponic systems may be particularly suitable in areas with environmental challenges, such as extreme temperatures or a lack of water resources (Benke & Tomkins, 2017; Somerville et al., 2014).

Hydroponic systems may use 80 to 99 percent less water than traditional soil-based planting systems (Verner et al., 2021), and because the systems are generally operated indoors, they offer decreased risks from weather-related shocks (Benke & Tomkins, 2017). Hydroponics is a potential solution for urban areas or locations with degraded soil or nonarable land (Benke & Tomkins, 2017; Somerville et al., 2014). Hydroponics may also allow growing seasons to be extended in areas with temperate climates (Gómez et al., 2019).

Although hydroponics is an advantageous method of production for several reasons, in many contexts, hydroponics requires higher startup costs than traditional agriculture (Verner et al., 2021). As noted by Gómez et al. (2019), indoor agriculture is energy-intensive, particularly in colder climates. In addition, although irrigation of crops in hydroponic systems requires less water, the relative water footprint of hydroponic systems (compared to traditional agriculture) is unknown because the hydroponic systems may use water for heating, cooling, and other purposes (Gómez et al., 2019). Also, certain types of hydroponic systems may be susceptible to water-borne pathogens (Maucieri et al., 2019). Additionally, aeroponic systems have mainly been used to grow small plants and have higher investment and management costs than other hydroponic systems (Maucieri et al., 2019; Verner et al., 2021; Tafesse et al., 2021).

Appendix B: The Operation of Aquaponic Systems

Aquaponic systems, which represent a small share of controlled environment agriculture (CEA) systems, integrate hydroponic crop systems with fish and other seafood production, including shrimp, crayfish, and other crustaceans (Somerville et al., 2014; Lennard & Goddek, 2019). In aquaponic systems, water and nutrients are usually recirculated between plants and seafood (Klinger & Naylor, 2012; Suhl et al., 2016).[35] Aquaponic systems offer the potential for more economically and environmentally sustainable production methods through the use of shared resources. However, because aquaponics requires the optimal use of inputs and conditions in multiple systems, economic and environmental outcomes from the integrated systems are not necessarily better than outcomes would be if the systems were operated without integration.

Water and Nutrients

Water and nutrient sources for aquaponic systems are essential to both nutrient delivery and to ensure that both plants and fish are in the optimal environment for growth and health (Lennard & Goddek, 2019; Somerville et al., 2014). Fish feed provides the primary source of nutrients through the system; plants obtain nutrients from the feed through fish waste (Somerville et al., 2014). In aquaponic systems, water passes through mechanical filters to remove sewage and sludge from the fish tanks (Somerville et al., 2014; Klinger & Naylor, 2012; Lennard & Goddek, 2019). Then, biofilters (beneficial bacteria) convert ammonia from the fish tanks into nitrates, which are required for plant production. Subsequently, the water, nitrates, and other nutrients are recirculated to the plant growth beds (which are configured in various ways).

Through this process, the water is purified by the plants, and the water (with some nutrients removed by the plants) returns to the fish tank, providing a suitable environment for the growth of fish (Klinger & Naylor, 2012). In aquaponics, most nutrients required for plant production are supplied from fish waste (Somerville et al., 2014). However, fish waste may not include all the nutrients necessary for optimal plant production. Aquaculture system operators must monitor and manage chemical, physical, and biological characteristics of water—including pH levels, levels of nitrogen, calcium, iron, magnesium, potassium, other nutrients, and water temperature and clarity (Somerville et al., 2014; Maucieri et al., 2019; Lennard & Goddek, 2019). Operators must add nutrients or make other adjustments as necessary to ensure the optimal environment for plants. Of course, different types of fish and plants have different nutrient and chemical needs.

Irrigation and Recirculation Systems

As in other hydroponic systems, deep water culture (DWC) and nutrient film technology (NFT) are widely used in commercial aquaponic systems (Somerville et al., 2014; Maucieri et al., 2019). In both DWC and NFT aquaponic systems, water flows through a filter from the fish tank and the tank or trough containing the plants' roots, then either back to the fish tank or the plant tank. Smaller-scale aquaponic systems often use the media bed technique, in which the growing medium that holds the plants' roots also acts as a water filter (Somerville et al., 2014). However, the media bed technique is relatively expensive for larger systems, and with higher fish stocking densities, additional filters may be necessary. NFT systems require less water per plant than DWC and media bed systems and require less labor for planting and harvesting (Somerville et al., 2014).

[35] Some "decoupled" aquaponic systems circulate water and nutrients from fish tanks to hydroponic systems but do not circulate water from the hydroponic systems to the fish tanks (Lennard & Goddek, 2019).

Opportunities and Challenges of Aquaponic Systems

Opportunities

The primary benefit of aquaponic systems is that the systems allow the coproduction of plants, fish, and other seafood. Otherwise, aquaponic systems provide the same benefits as other hydroponic systems.

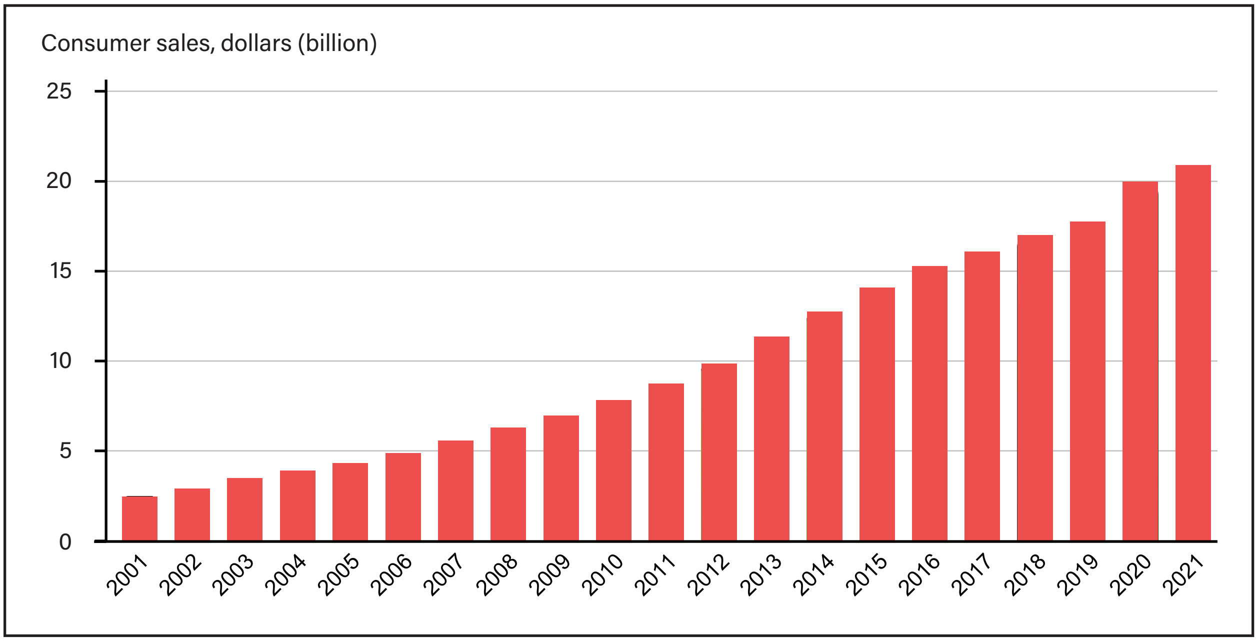
Challenges

Startup and maintenance costs for aquaponic systems are high relative to both soil-based plant production and hydroponic systems (not including fish). As noted by Lennard & Goddek (2019), since both hydroponic systems and aquaculture systems are productive and effective, coupling or linking the systems as aquaponics may result in productivity losses. Aquaponic system operators must have broader knowledge about the biological and chemical requirements of their systems than operators of nonfish hydroponic or nonplant aquaculture systems—including knowledge about the fish, plants, and beneficial bacteria that comprise the systems (Somerville et al., 2014).

Appendix C: The Organic Designation of Hydroponic and Aquaponic Crops

According to Nutrition Business Journal estimates, retail sales of U.S. organic fruits and vegetables experienced strong annual growth rates over the last two decades, reaching $21 billion in consumer sales in 2021 (figure C.1). As consumer demand for organic fruits and vegetables grew, the organic industry has continued to discuss the role of container systems in organic production.

Figure C.1
Fruit and vegetable sales growth in the U.S. organic retail food market, 2001–21



Source: USDA, Economic Research Service using data from the Nutrition Business Journal, 2022.

What is Organic?

Congress enacted the Organic Foods Production Act of 1990 (OFPA) under Title 21 of the 1990 Farm Bill to establish uniform standards for organic agricultural products (Organic Foods Production Act, 1990). The final regulations implementing the USDA National Organic Program (NOP) became effective in 2002 (National Organic Program, 2000). In the United States, food labels that make an organic claim or use the USDA organic seal must follow USDA organic regulations. One of the requirements for producers of organic products is organic certification[36] from a USDA-accredited certifying agent. Organic certification verifies that a farm or handling facility complies with organic standards, providing assurance to consumers of the organic product's integrity.[37]

The USDA organic regulations define organic production as the integration of "cultural, biological, and mechanical practices that foster cycling of resources, promote ecological balance, and conserve biodiversity" (National Organic Program, 2000). The regulations prohibit materials (published in the USDA, Agricultural Marketing Service National List of Allowed and Prohibited Substances) commonly used in conventional

[36] Some products may be labeled organic but are exempt from the requirements for third-party certification. See 7 C.F.R. Part 205.101 for exemptions and exclusions to organic certification.

[37] For additional background information on USDA organic labeling regulations, see Kuchler et al. (2017).

agriculture, including many synthetic fertilizers, insecticides, herbicides, and fungicides (Raszap-Skorbiansky et al., 2021). USDA organic regulations also prohibit the use of genetically modified organisms (GMOs). Since the USDA organic regulations became effective, agricultural production systems and consumers' understanding of "organic" have continued to evolve, leading to regulatory updates and policy clarifications.

Previous Discussions on Container Systems in the Organic Community

In the past, the National Organic Program has defined container systems using the "NOP memo" (USDA, 2019) definition of container systems, which defines the systems as "container, hydroponic, and other plant pot-based systems with or without soil as the growing media."

Over the past 20 years, there have been active discussions within the National Organic Standards Board (NOSB) and within the organic industry regarding organic certification of container systems. The NOSB is a Federal Advisory Board established by the OFPA and comprises public volunteers from across the organic community. The NOSB considers and makes recommendations for new requirements, regulatory changes, and additional guidance. While not considered policy, NOSB recommendations are taken under consideration when the National Organic Program develops guidelines or initiates rulemaking.

In 2010, the NOSB passed a formal recommendation titled *Production Standards for Terrestrial Plants in Containers and Enclosures* (NOSB, 2010). The 2010 NOSB recommendation stated that soilless production systems (like hydroponics and aeroponics) should not be eligible for USDA organic certification. The recommendation explained that systems that lack soil-plant ecology would not meet the soil fertility requirements in OFPA and USDA organic regulations. Following the 2010 NOSB recommendation, the National Organic Program did not initiate rulemaking to specifically address hydroponic or aeroponics.

NOSB members continued to discuss how innovative systems (like hydroponics, aeroponics, and aquaponics systems) align with organic production, following the NOSB's 2010 recommendation. In 2016, NOSB released a detailed Hydroponic and Aquaponic Task Force Report (NOSB, 2016). While the dialogue on container systems in the report and subsequent meetings covered a multitude of topics, the overarching concern was the lack of soil in some hydroponics, aeroponics, and aquaponics systems (NOSB, 2017). Overall, some members of the organic community concluded that production systems that eliminate soil ecology should not be able to label their food as organic in the United States.

In response to further discussions within the broader organic community, the National Organic Program issued a clarifying announcement in January 2018 (USDA, 2018):

"Certification of hydroponic, aquaponic, and aeroponic operations is allowed under the USDA organic regulations, and has been since the National Organic Program began. For these products to be labeled as organic, the operation must be certified by a USDA-accredited certifying agent, and maintain compliance with the USDA organic regulations."

The controversy surrounding USDA-certified organic hydroponic, aquaponic, and aeroponic operations led to legal action. In 2019, the National Organic Program received a rulemaking petition that requested rulemaking specifically prohibiting hydroponic operations from obtaining USDA organic certification (CFS, 2019). The USDA denied the petition in the summer of 2019. The following year, a lawsuit was filed against the USDA related to the denial of the rulemaking petition and a prohibition of organic certification for production systems that grow food without soil. On March 19, 2021, a U.S. District Court ruling upheld the National Organic Program's previous petition denial to prohibit hydroponic systems (Seebord, 2021). At the time of this writing, there is no National Organic Program policy (nor USDA organic regulation) that specifically prohibits container systems including hydroponic, aquaponic, or aeroponic.