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Geographically Dependent Sustainability Indicators for Comparison of Conventional Vegetable Production to Controlled-Environment Agriculture

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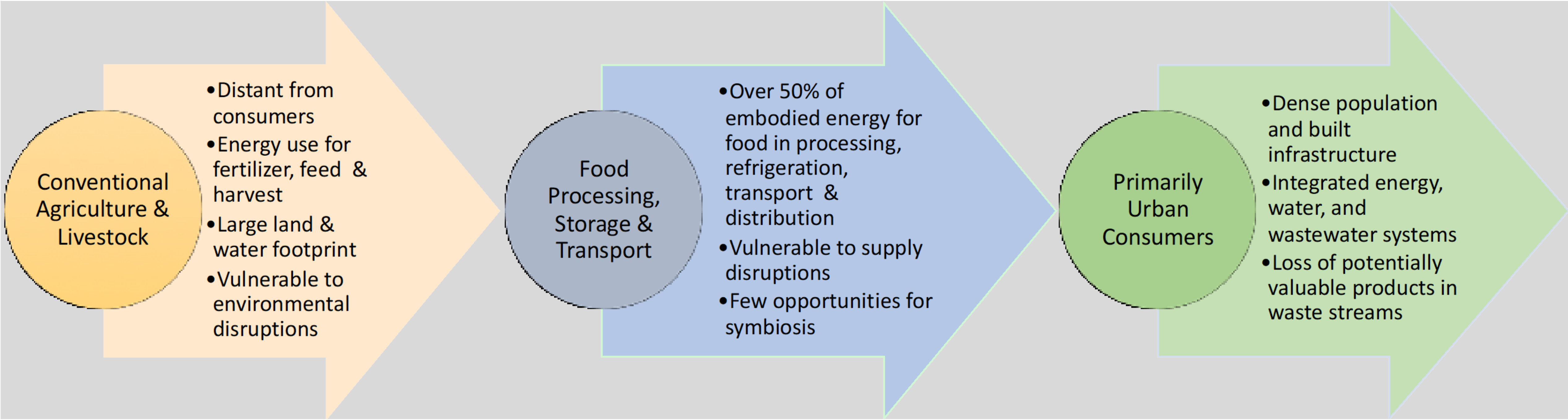


To fully understand the challenges and opportunities for sustainability of the agricultural system, it is necessary to understand the role of location in the Food-Energy-Water-Sustainability (FEWS) nexus.

Outline

1. Vegetables in the current food supply chain
2. Growing vegetables in controlled-environment agriculture (CEA) farms with a focus on plant factories
3. Food access implications of CEA vegetable production.
4. Geography and water sustainability
5. Resilience, Energy and Greenhouse Gas (GHG) implications of CEA.

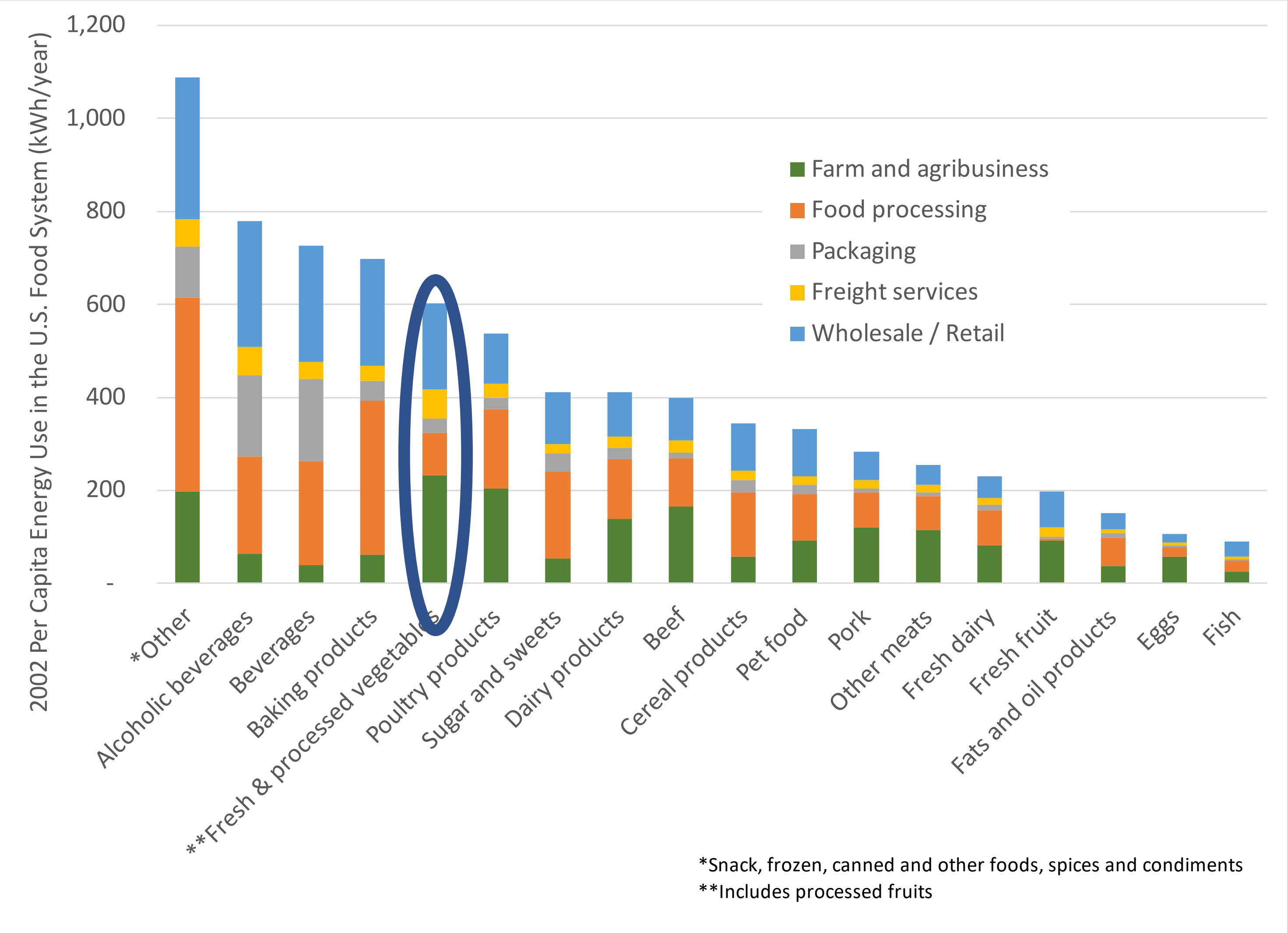
1. Vegetables in the current food supply chain

Per capita, vegetable production requires the most on-farm & transport energy use in the U.S. food system.

The current per capita supply of fresh vegetables requires;

- **20 m² of land**
- **400 kWh of energy**
- **16,500 L of water**

Sources: Canning et al. 2010, ("USDA ERS - Food Availability (Per Capita) Data System" 2020), ("USDA/NASS QuickStats Ad-Hoc Query Tool" 2021



Per capita distribution of energy use among food categories and supply chain stages (kilowatt-hours per year [kWh/year]) in 2002.
Source: Canning et al. 2010*; NREL Analysis.

*This study is dated, but is comprehensive and frequently referenced as a basis for other work

2. Growing vegetables in controlled-environment agriculture (CEA) farms with a focus on plant factories

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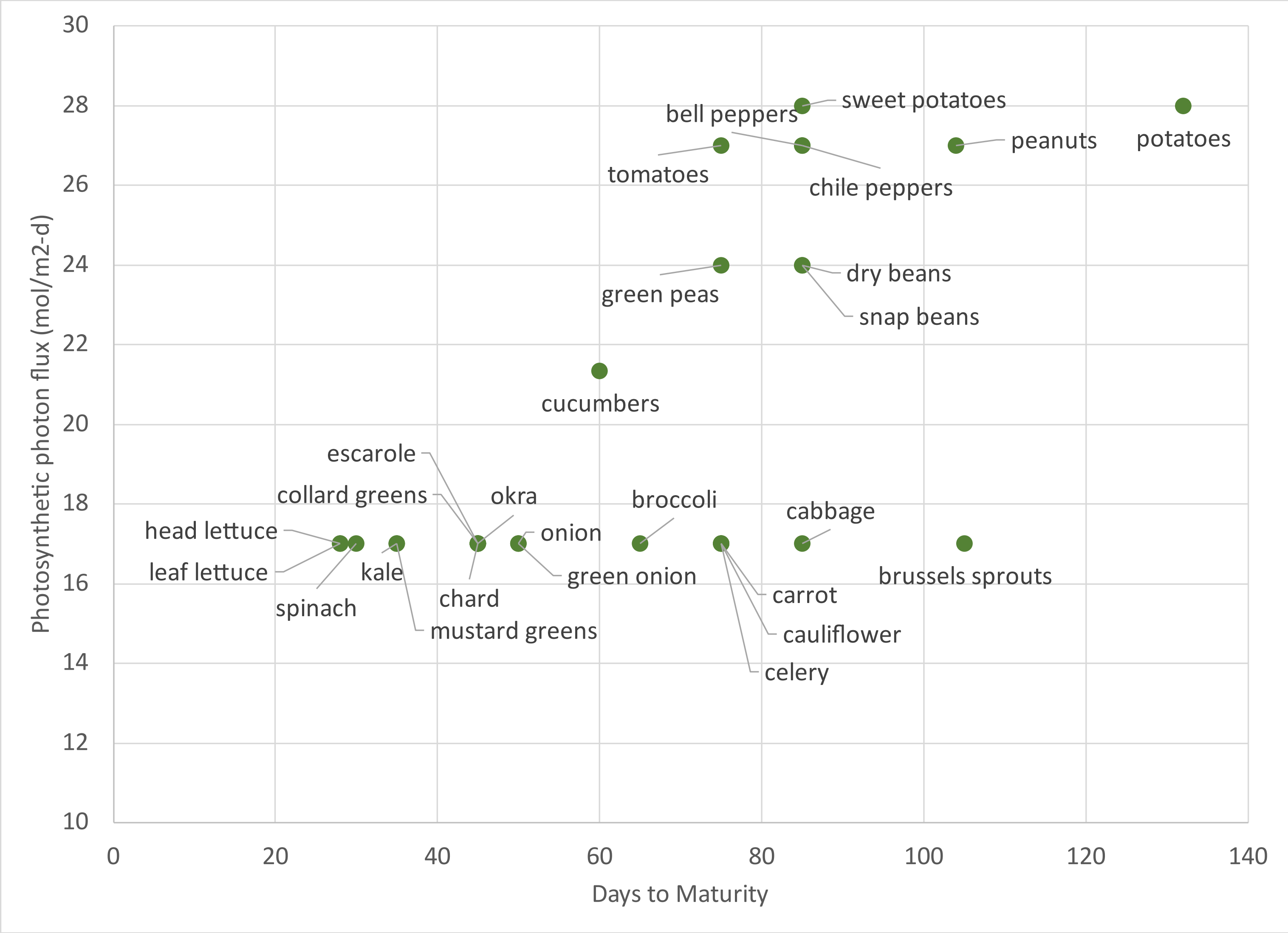
Criteria for CEA Production

- Do not require soil
- Have a relatively small total plant volume to produce volume ratio
- Are not too tall
- Do not require a rest or cold period (e.g., asparagus requires a period of freezing temperatures)*
- Have moderate light requirements/days to maturity
- Are "profitable" to grow
- Are already grown to maturity in greenhouses
- Are already grown in plant factories

*https://www.agmrc.org/commodities-products/vegetables, PPF values (http://www.projectrho.com/public_html/rocket/supplement/CR-2004-208941.pdf)



Lighting consumes the highest fraction of energy in plant factories. The total amount of energy consumed per kg of produce is a function of the photosynthetic photon flux required by the plant and the days to maturity.

Vegetables Assumed to be Grown in CEA Plant Factories (PF vegetables) for this Study

- Represent 41% of all vegetable primary production weight
- 39% of current consumer availability by weight
- 46% of the types of vegetables grown (17 of 37)*
- PF vegetable production would eliminate nearly 30 kg/year/person of supply chain waste.

*Tracked in Vegetables and Pulses Yearbook (USDA 2020)

Current food system per capita production and losses for PF vegetables in this study. Data Source (USDA 2020)

PF Vegetable	Current Food System Primary Production (kg/year)*	Availability Adjusted for all Losses (kg/year)	Losses Farm Gate to Retail (%)	Losses at Consumer Level (%)	PF Vegetable Production Needed to Supply Retail Weight (kg/year)
dark green	**11.91**	**5.25**	**27%**	**40%**	**8.72**
broccoli	3.83	1.95	19%	37%	3.11
collard greens	0.38	0.07	51%	65%	0.19
escarole	0.08	0.02	53%	35%	0.04
kale	0.48	0.12	35%	62%	0.31
leaf lettuce	5.50	2.46	26%	40%	4.08
mustard greens	0.31	0.06	66%	42%	0.11
spinach	1.20	0.55	30%	34%	0.84
turnip greens	0.14	0.02	67%	57%	0.05
other	**15.66**	**7.29**	**23%**	**40%**	**12.10**
brussels sprouts	0.37	0.25	13%	21%	0.32
cabbage	2.93	1.47	19%	38%	2.36
cauliflower	1.40	0.43	26%	58%	1.04
cucumbers	5.14	2.01	32%	43%	3.50
head lettuce	5.56	3.03	15%	36%	4.74
okra	0.26	0.09	47%	31%	0.14
red & orange	**47.14**	**18.05**	**48%**	**26%**	**24.45**
bell peppers	5.07	2.08	18%	50%	4.16
chile peppers	3.10	2.04	31%	4%	2.13
tomatoes	38.98	13.93	53%	23%	18.17
Grand Total	**74.71**	**30.58**	**39%**	**32%**	**45.27**

*Current food system per capita values for vegetables grown in plant factories for this study

PF Farm Model – Energy Use

- Lighting; (1)

$$\sum_i^n \left(0.15\frac{kWh}{mol} * PPF\left(\frac{mol}{m2\ d}\right)_i * \frac{days\ i}{yield_i} * kgi\right)$$

- *Efficiency gains for wavelength tuned LED and light pulsing reduce energy use for lighting by >40% in comparison to fluorescent.* (2)

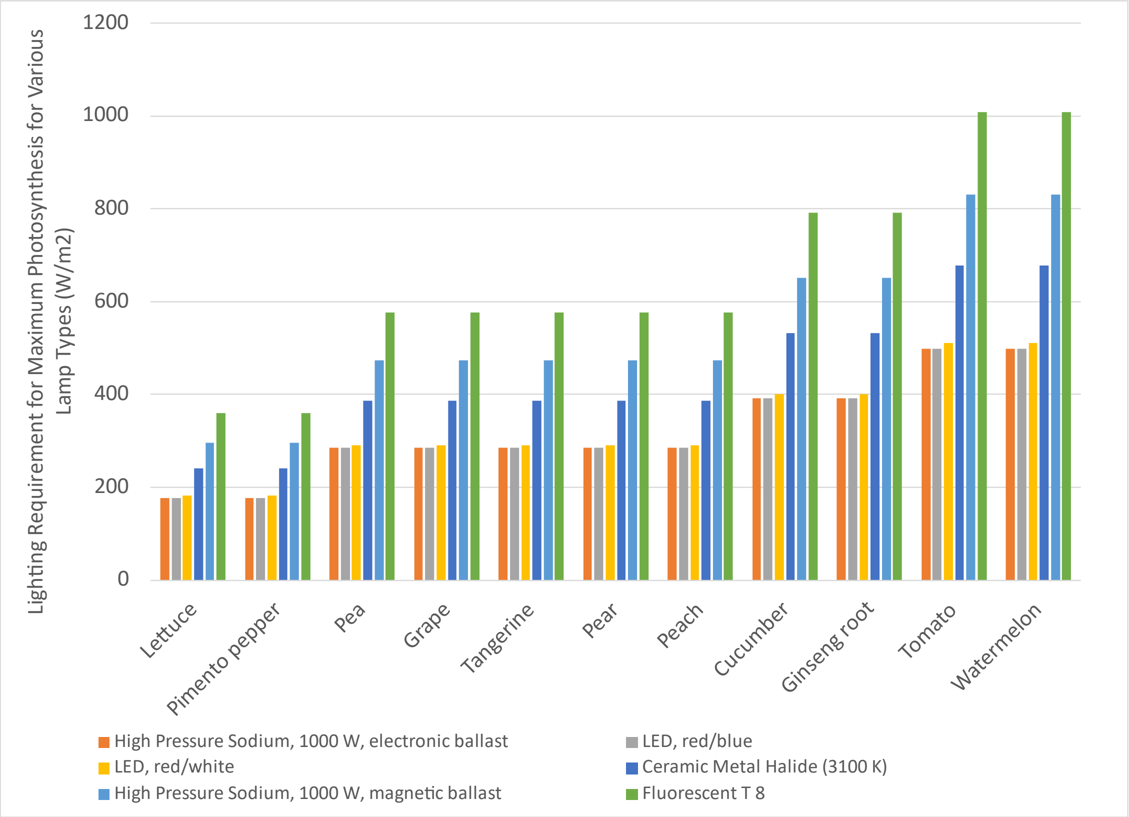
- Cooling is a linear function of the lighting energy use; (3)

$$\sum_i^n \left(0.28 * lighting \left(\frac{kWh}{kg}\right)_i - 0.039\right) * kgi$$

- *HVAC integration with buildings could save 18 – 30% of heating and cooling energy use.* (4)

- Mechanical energy use is based on the footprint; (3)

$$\sum_i^n \left(\frac{5.68\frac{kWh}{m2}}{yield_i\left(\frac{kg}{m2}\right)} * kgi\right)$$



Lighting requirements for various crops (W/m2). Sources; O'Sullivan et al. 2019, NREL Analysis

Sources; 1. red/green LED with 10% pulsing efficiency gain. Hanford 2004; Martin, Poulikidou, and Molin 2019; Avgoustaki and Xydis 2020; Barbosa et al. 2015; Nelson and Bugbee 2014; 2. Olvera-Gonzalez et al. 2021; 3. Adenaeuer 2014; O'Sullivan et al. 2019; Benis, Reinhart, and Ferrão 2017a; Despommier 2013; Benis, Reinhart, and Ferrão 2017b; Van Ginkel, Igou, and Chen 2017; Graamans et al. 2018; Hanford 2004; Bao et al. 2018. 4. Sanyé-Mengual et al. 2018

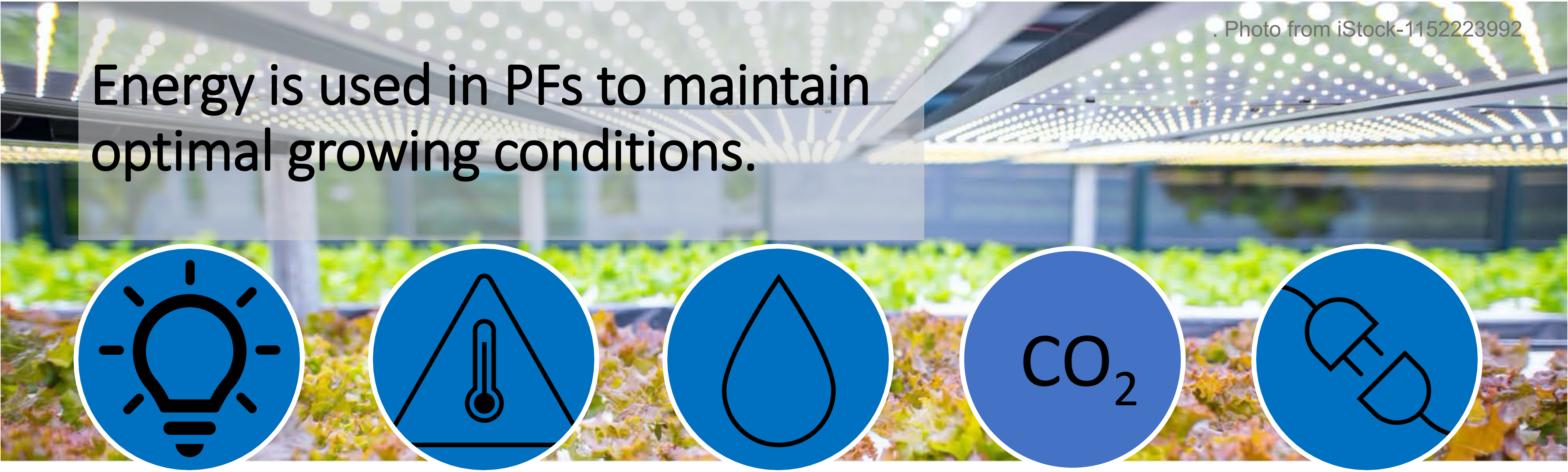
PF Farm Model – Nutrient Use & Recovery

Values (g/person/year)	Recovery from Wastewater (g/person/year)[1]	Concentration in Wastewater (mg/L) & Recovery (%)	Requirement for CE Farms Producing the 2018 Supply of CE Amenable Vegetables (g/person/year)[2]
Nitrogen (N)	3,453	N 42.3 (89% recovery), NH_3 24.8 (93% recovery)	26
Phosphorus (P)	252	P 3.3 (97% recovery), PO_4 3.1 (98% recovery)	12
Potassium (K)	0		29

1. 167 L/person/day wastewater production
2. $\sum_i^n kg\ CE\ productioni * \left(\frac{L}{kg}\right) i * (\frac{g}{L}\ nutrient)$, 0.105 g/L N, 0.047 g/L P, 0.117 g/L K

Sources: Van der Hoek, Duijff, and Reinstra 2018, Perera and Englehardt 2020, Hanford 2004

Energy is used in PFs to maintain optimal growing conditions.



. Photo from iStock-1152223992

Lighting

Modeled system; high-efficiency light emitting diode (LED)

***16 kWh/kg**

710 kWh/person/yr

Heating, Cooling & Humidity Control

Modeled system assumes cooling only.

****3 kWh/kg**

140 kWh/person/yr

Water Use

***8 L/kg**

360 L/person/yr

CO_2 concentration

Slightly elevated CO2 concentrations through integration with an occupied building

0.2 kg CO2 required/kg

Mechanical

Energy is used for mechanical and control equipment.

0.07 kWh/kg

3 kWh/person/yr

* Includes 10% efficiency gain with pulsing. **Highly variable depending on climate and building integration extent

Sources; Hanford 2004; Martin, Poulikidou, and Molin 2019; Avgoustaki and Xydis 2020; Barbosa et al. 2015; Nelson and Bugbee 2014; Olvera-Gonzalez et al. 2021; Sanyé-Mengual et al. 2018; (Adenaeuer 2014; O'Sullivan et al. 2019; Benis, Reinhart, and Ferrão 2017a; Despommier 2013; Benis, Reinhart, and Ferrão 2017b; Van Ginkel, Igou, and Chen 2017; Graamans et al. 2018; Hanford 2004; Bao et al. 2018

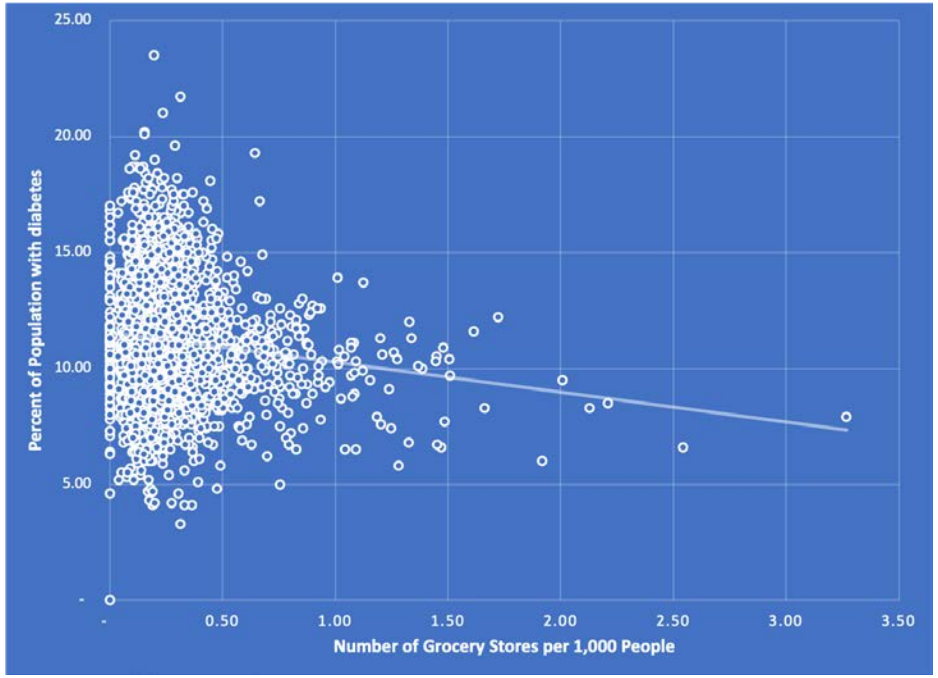
3. Food access implications of CEA vegetable production.

Diabetes is a metabolic disorder linked to diet that is tracked by the USDA as an indicator of food access, food security, and diet quality.

The Food Environment Atlas is unique in providing geographically-resolved data linking food access metrics to health

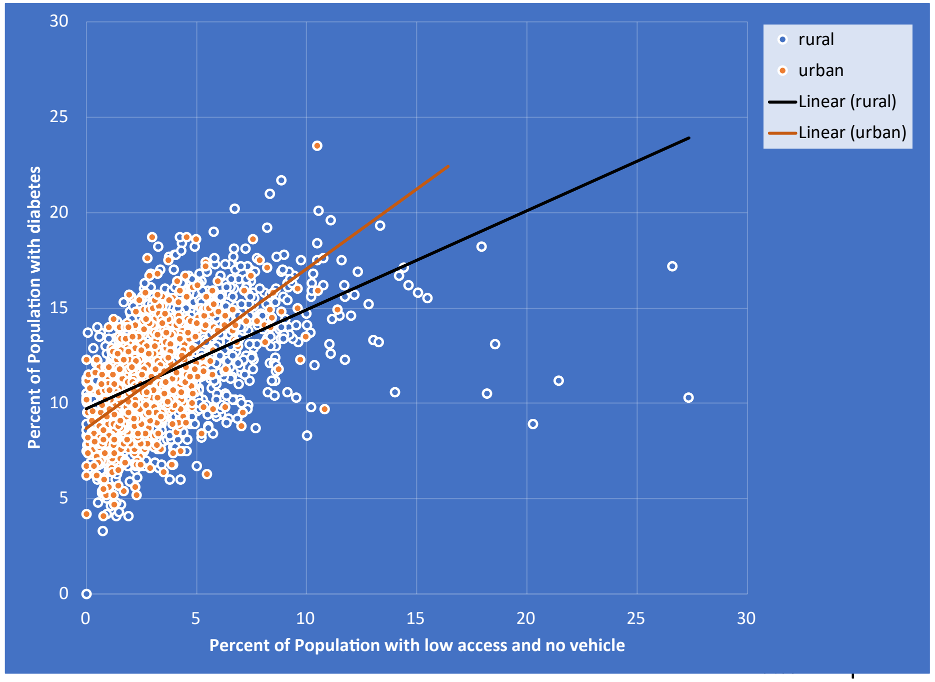
Data Source; Food Environment Atlas, https://www.ers.usda.gov/data-products/food-environment-atlas/, accessed 11/18/2021

Weak correlation between diabetes rates & availability of grocery stores for all populations.



Diabetes rates are more strongly correlated with low-income populations with low access to grocery stores who also do not have access to a vehicle

- URBAN; y = 0.84x + 8.69
  $R^2 = 0.3226$
- RURAL; y = 0.52x + 9.71
  $R^2 = 0.2666$



A Food Diversity Index Captures Vegetables' Dietary Importance & CEA's Local Benefits

- Metrics that assess food nutrient content may not capture vegetables' dietary benefits
  - E.g., the Nutrient Density Score typically measures protein, fiber, calcium, iron, and vitamins A and C. Many vegetables are not high in protein or calcium but contain a variety of micronutrients. (Gustafson, et al. 2016)
- The Shannon Diversity Index measures the variety of foods available to consumers[1].
  - Well suited to analysis of the value of community-level CEA PFs.
  - Excludes staple crops defined as cereals, roots, tubers, and bananas/plantains

SDI $$Shannon\ Diversity = -\sum_i s_i \ln(s_i)$$

Where *Si* is the fraction by weight of the *ith* food item.

Normalized to a 0 to 100 scale using a multiplier of 100/Ln(N), where N = the total number of foods available.

Store Type	Number of vegetables	SDI
Entire U.S. vegetable supply	36	79
Grocery offering top 80% (by wt) of U.S. vegetables	12	55
CEA plant factory	17	38
Convenience store grocery[2]	5 - 6	25 - 26

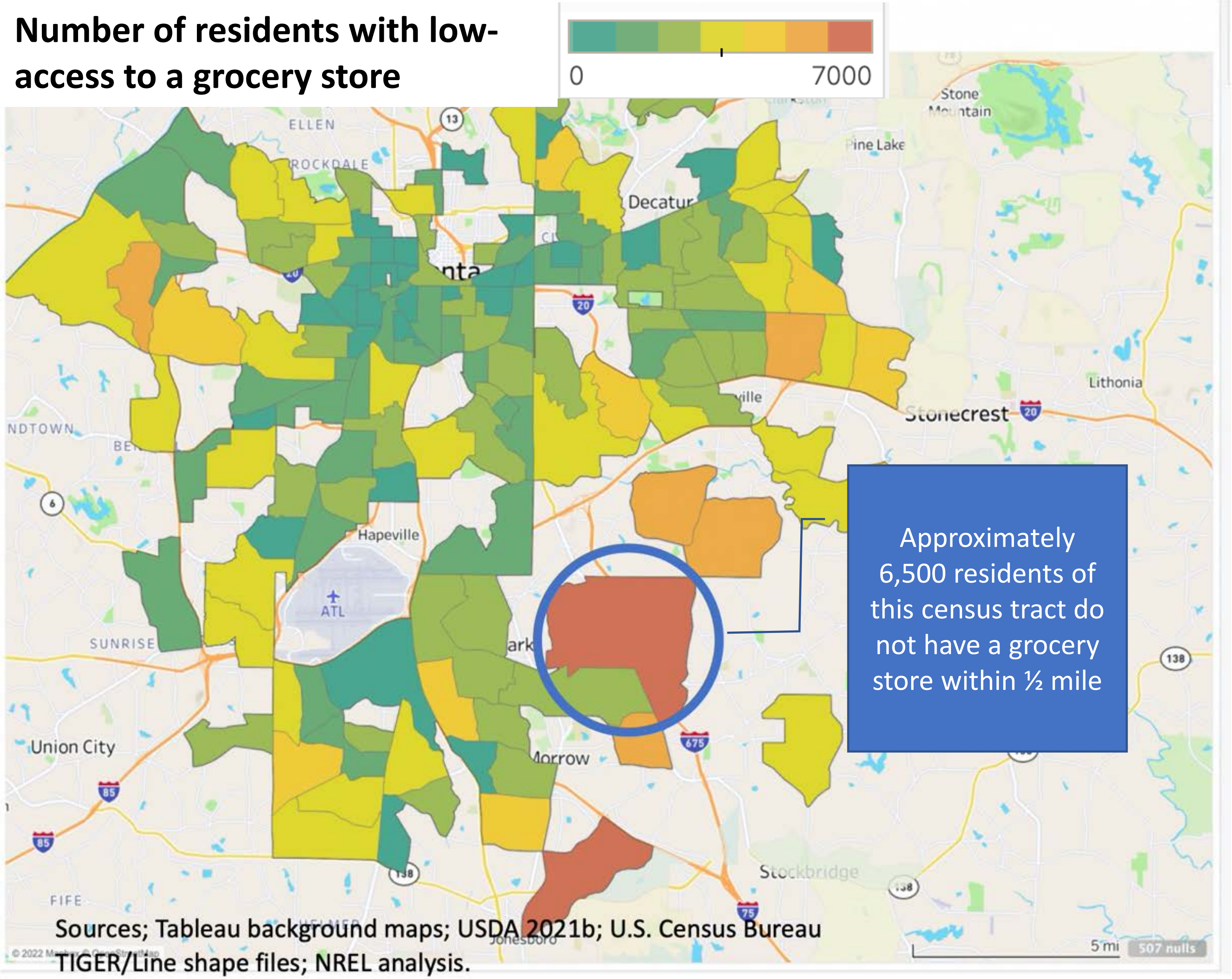
1. (Gustafson, et al. 2016) Gustafson, D., A. Gutman, W. Leet, A. Drewnowski, J. Fanzo, and J. Ingram. 2016. "Seven Food System Metrics of Sustainable Nutrition Security." Sustainability (Switzerland) 8 (3). https://doi.org/10.3390/su8030196.
2. Vegetables offered at some Dollar General stores (https://www.winsightgrocerybusiness.com/fresh-food/dollar-general-growing-its-fresh-produce-program-Arkansas)

PF vegetable production could be located in communities with low access to grocery stores

PF vegetable production to serve 6,500 residents:

- 293 Mg vegetable production.
- 5,600 MWh electricity.
- 4,450 m^2 PF footprint.
- 2,340 m^3 water

Sources; Batstone et al. 2015; Cai, Park, and Li 2013; Ye et al. 2020; Theregowda et al. 2019; Wu and Vaneeckhaute 2022; Perera and Englehardt 2020; Rahimi et al. 2019; Van der Hoek, Duijff, and Reinstra 2018; NREL analysis



Food Availability Atlas Data for Atlanta; Population Without Access to a Grocery Store Within Walking Distance (~ ½ mile).

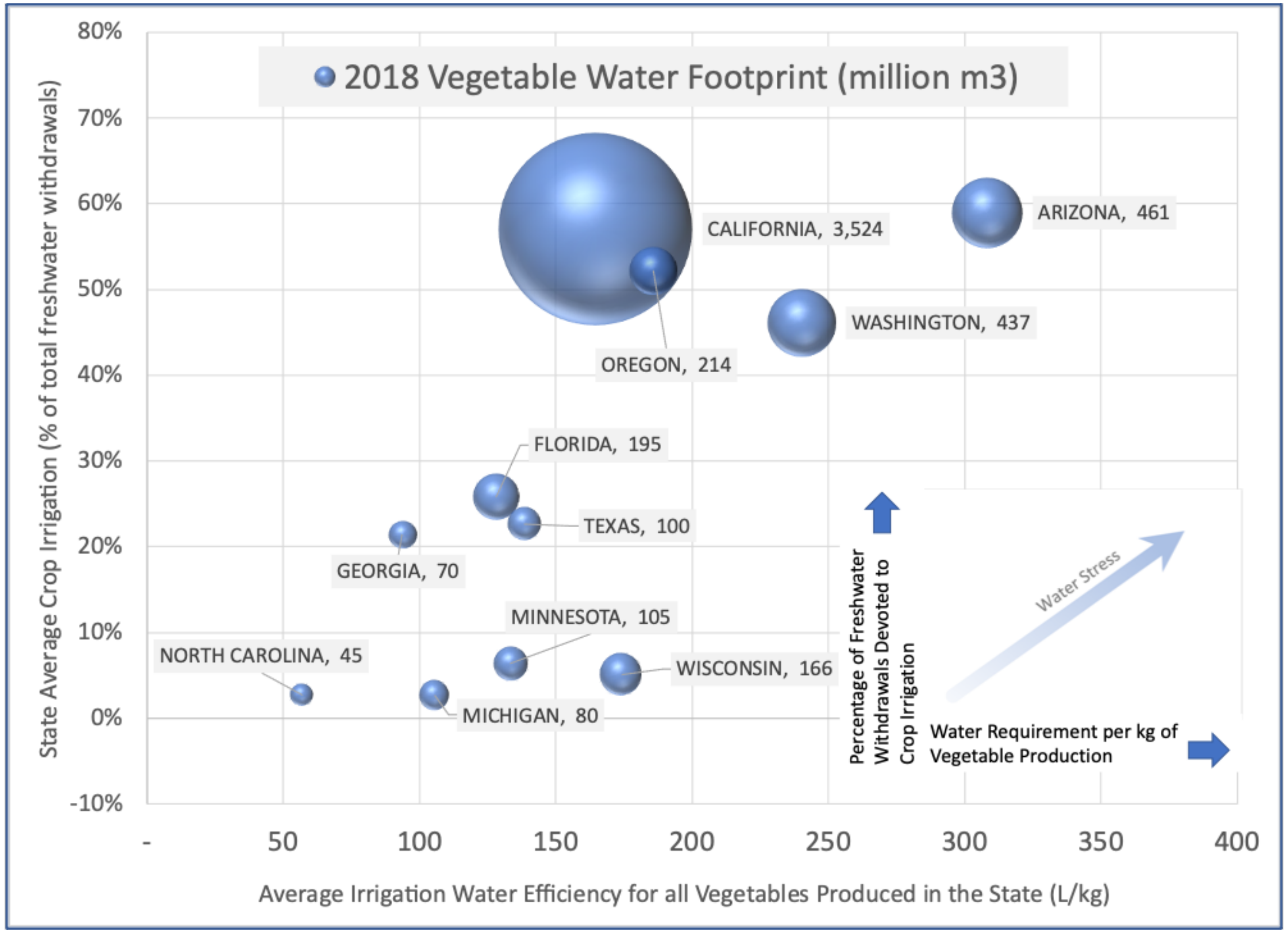
4. Geography and Water Sustainability

Vegetable crop irrigation accounted for only 2% of freshwater withdrawals nationwide, but those withdrawals are concentrated in water-stressed regions.

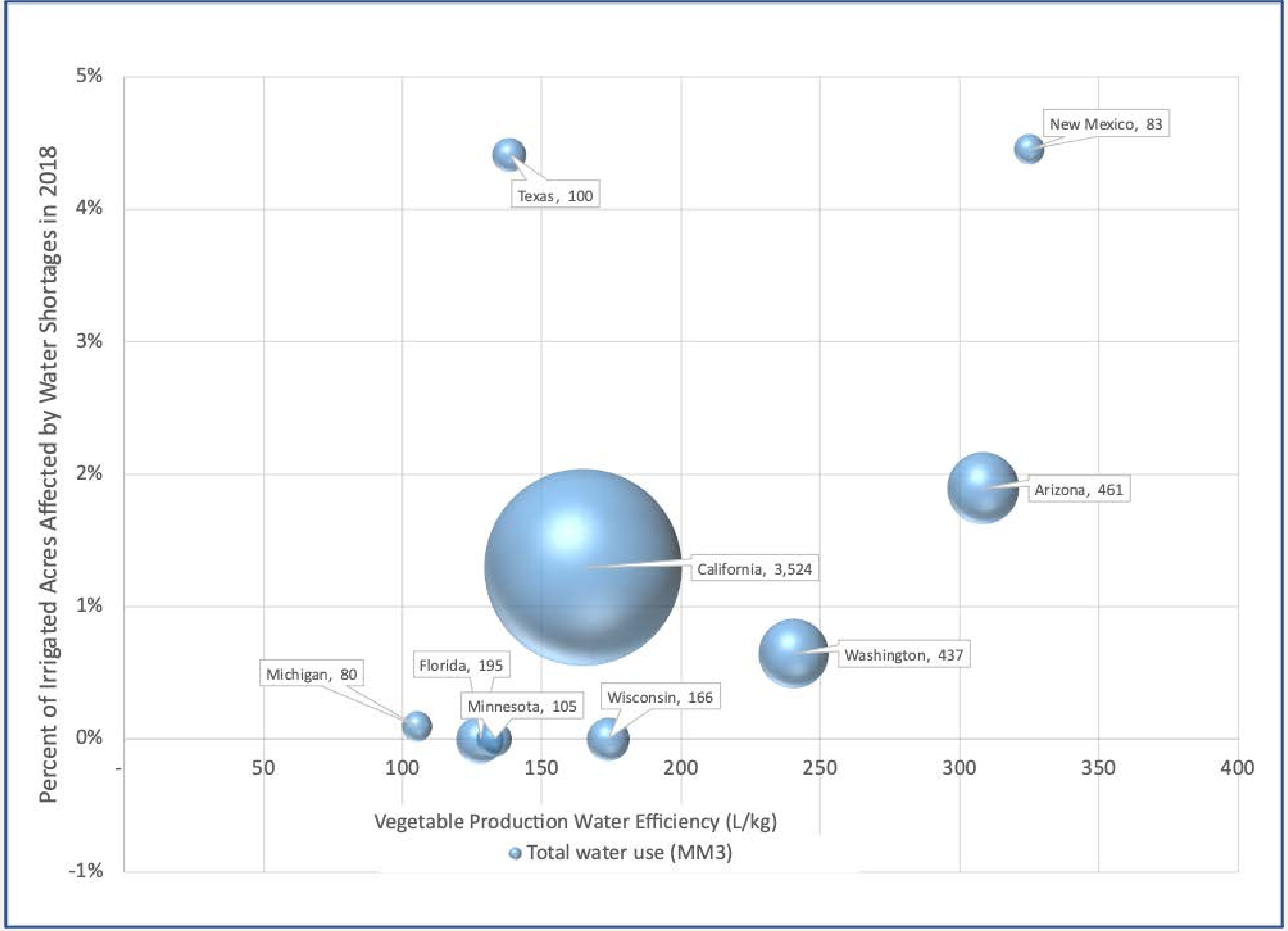
Per capita PF vegetable production requires ~360 liters

Field production of the same vegetables requires ~9,200 liters

Sources: Dieter and Linsey 2017, https://www.nass.usda.gov/Publications/AgCensus/2017/Online_Resources/Farm_and_Ranch_Irrigation_Survey/index.php, NREL analysis



Most vegetables are grown in water-stressed regions in the western United States.



Irrigation curtailment percent of total irrigated acres in 2018.

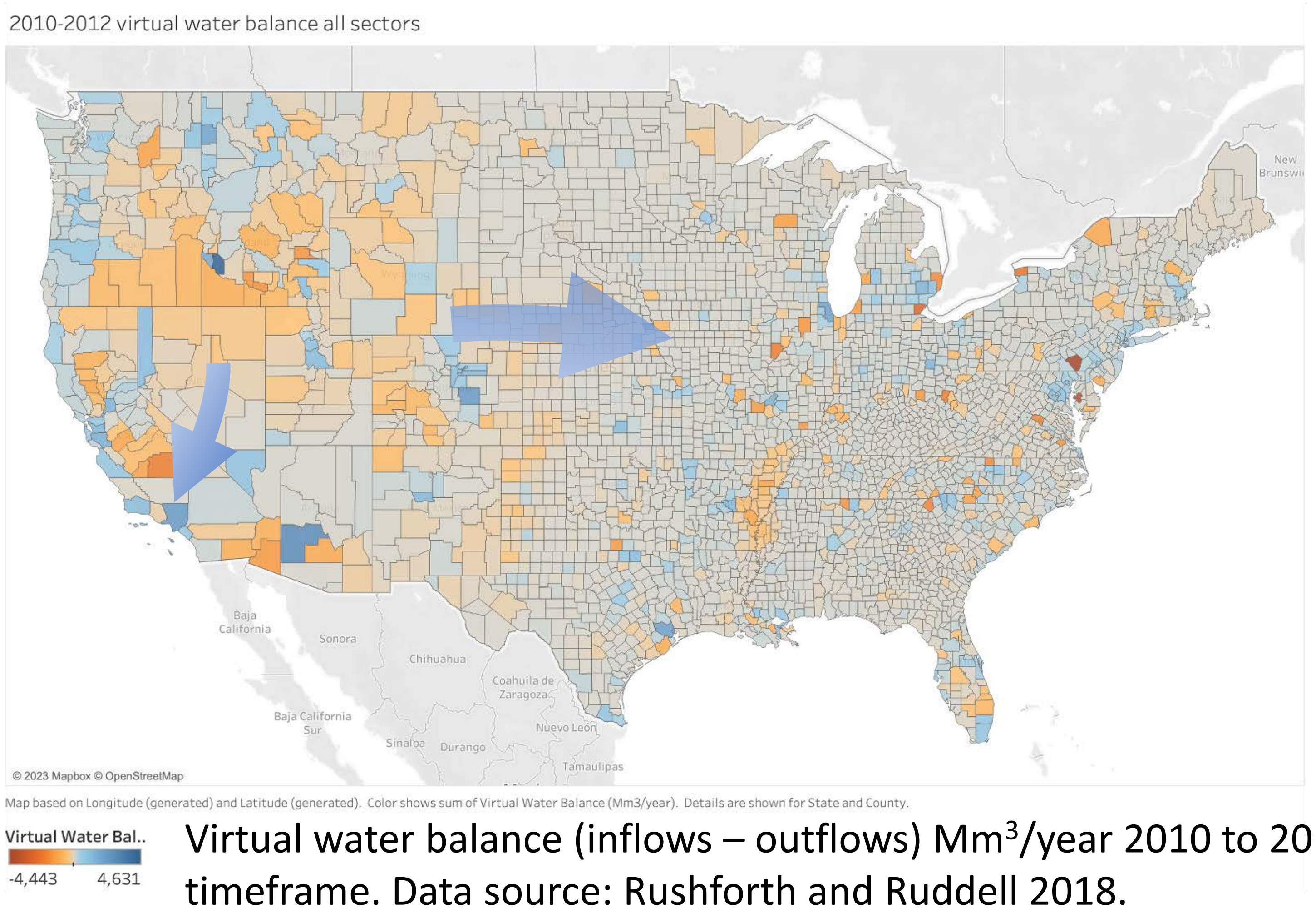
The percentage of acres affected by water shortages is another measure of water stress

Water footprint and virtual water flows

Water footprint = total withdrawals + net virtual water (virtual water inflow – virtual water outflow)

Sectors

- Power
- Irrigated agriculture
- Livestock
- Industrial
- Mining
- Domestic



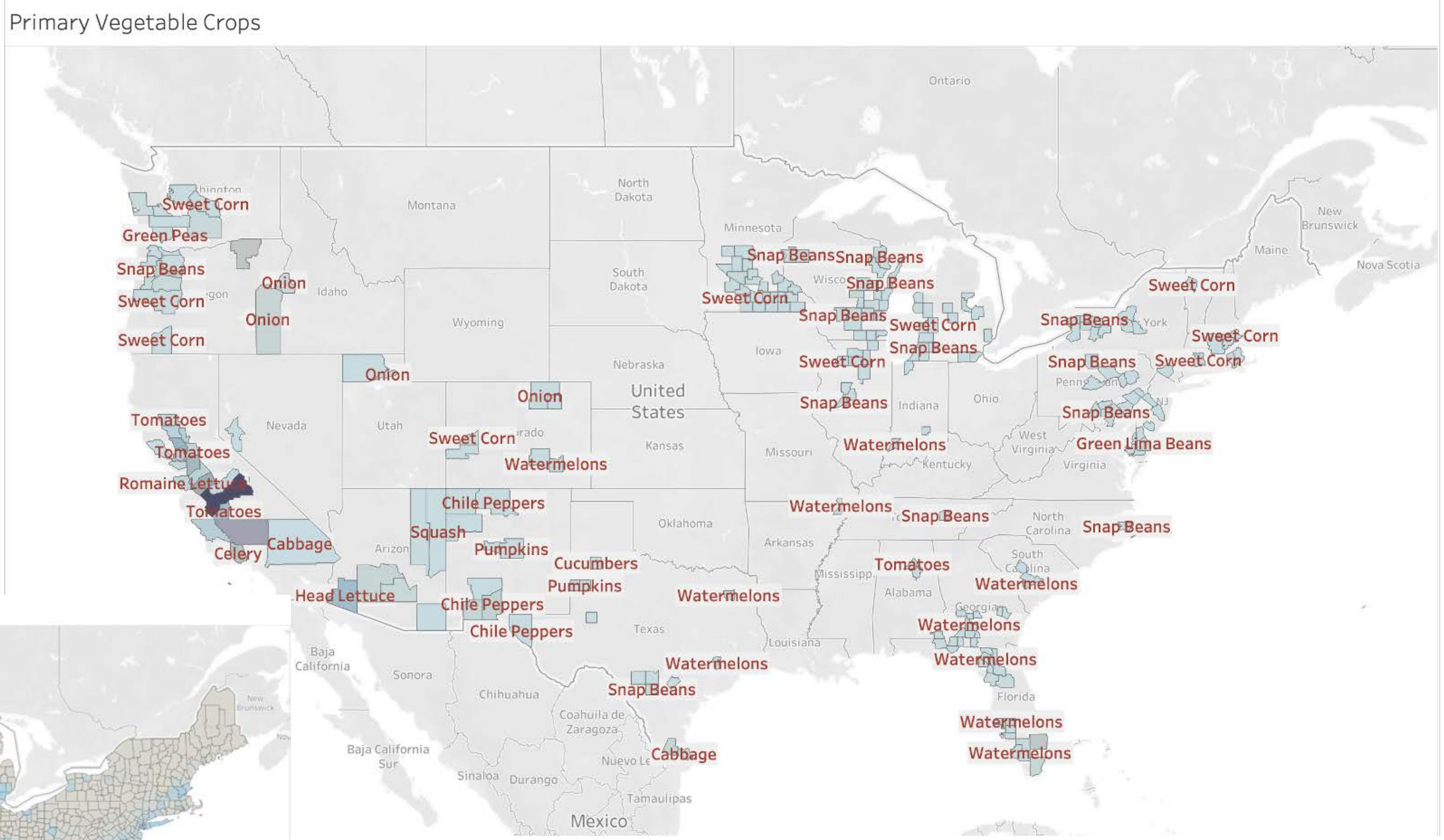
Virtual water balance (inflows – outflows) Mm^3/year 2010 to 2012 timeframe. Data source: Rushforth and Ruddell 2018.

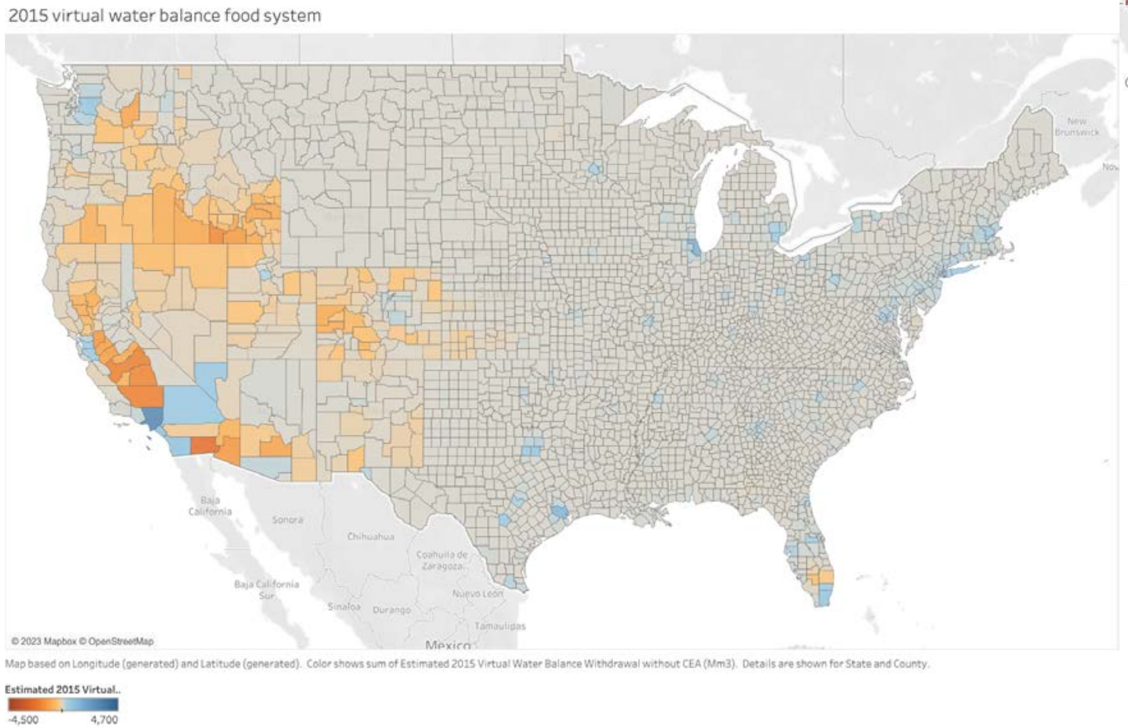
Virtual water flows from red areas to blue areas

- Virtual water flows into urban areas
- Virtual water flows from west to east

Virtual Water Flows – Food System

Virtual water flows estimated for 2015 for livestock and crop irrigation

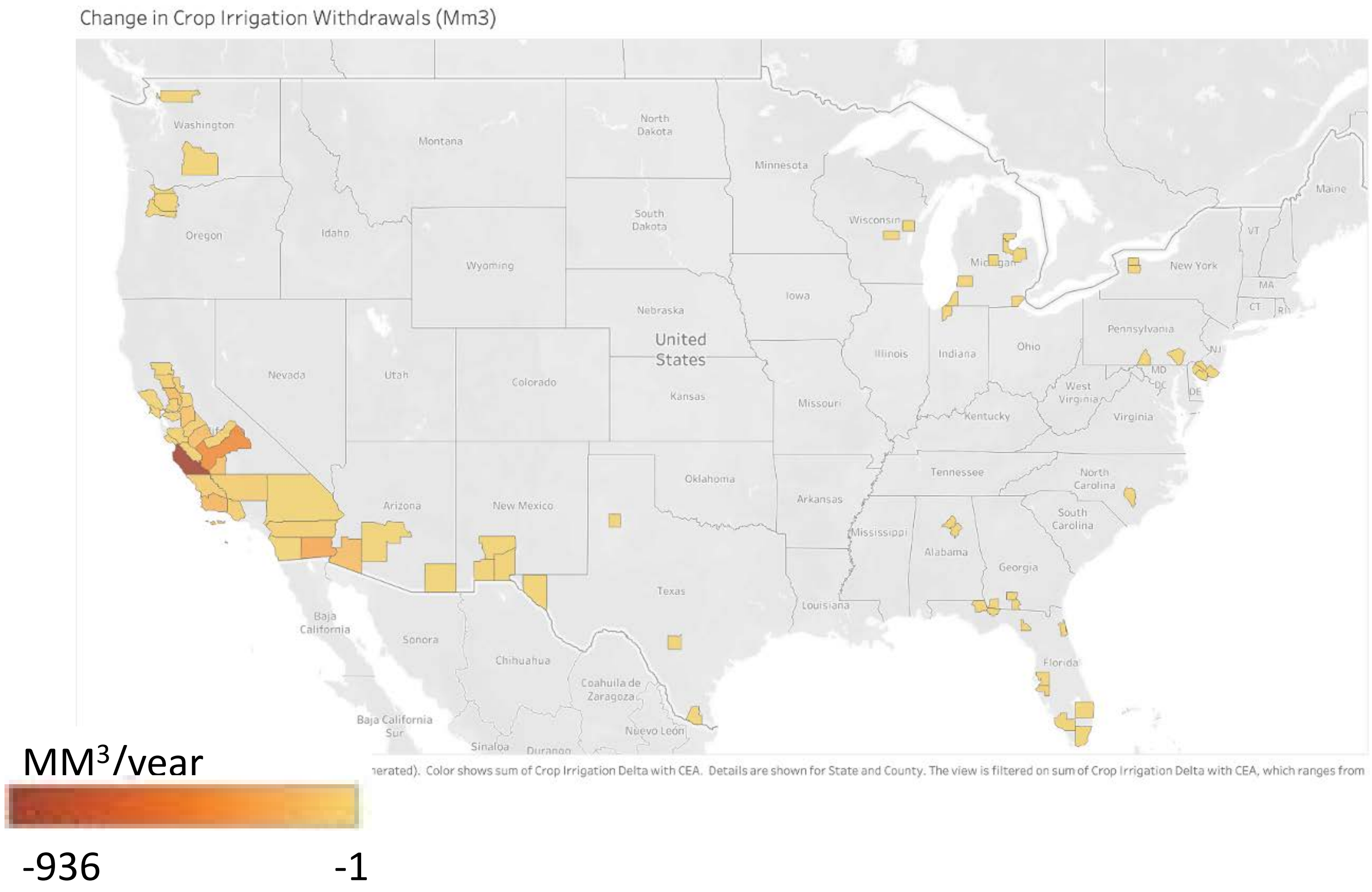




Primary vegetable crops grown in each region

With PFs, vegetable production moves to distributed CEA farms near consumers

- Water withdrawals for field irrigation would be reduced by the amount needed to grow the PF vegetables.
- Water withdrawals for vegetable production in PFs would occur near consumers (i.e., distributed by population)
- Total water withdrawals would be reduced because of the high water-efficiency of PF production

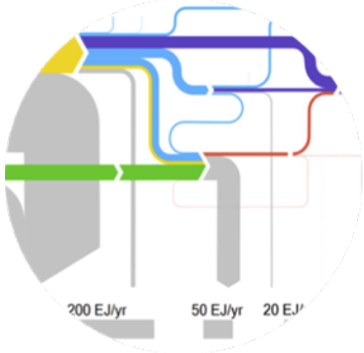


Change in crop irrigation water withdrawals with PF vegetable crops grown near consumers. CEA plant factories would reduce water withdrawals by ~3 billion m3/year in water-stressed regions of the country.

5. Resilience, & Energy implications of CEA.

City Foodshed

~2,000 m^2 of agricultural land is required to support a person with a typical diet[1]



Energy

On an energy basis, just 9% global agricultural dry biomass consumed as food[2]

Waste Streams

Atlanta, Georgia's wastewater could supply 348x the nutrients needed to supply the city's fruits & vegetables[3]

CEA PFs in urban contexts offers integration of energy systems to maximize efficiency, use of waste heat and opportunities for renewables

1. Zasada, et al. 2019, 2. (Lupton and Allwood 2018 3. Van Ginkel et al. 2017

Municipal wastewater contains more than enough recoverable nitrogen and phosphorus to supply nutrients for CEA cultivation of vegetables for the population.

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1. 167 L/person/day wastewater production
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Sources: Van der Hoek, Duijff, and Reinstra 2018, Perera and Englehardt 2020, Hanford 2004

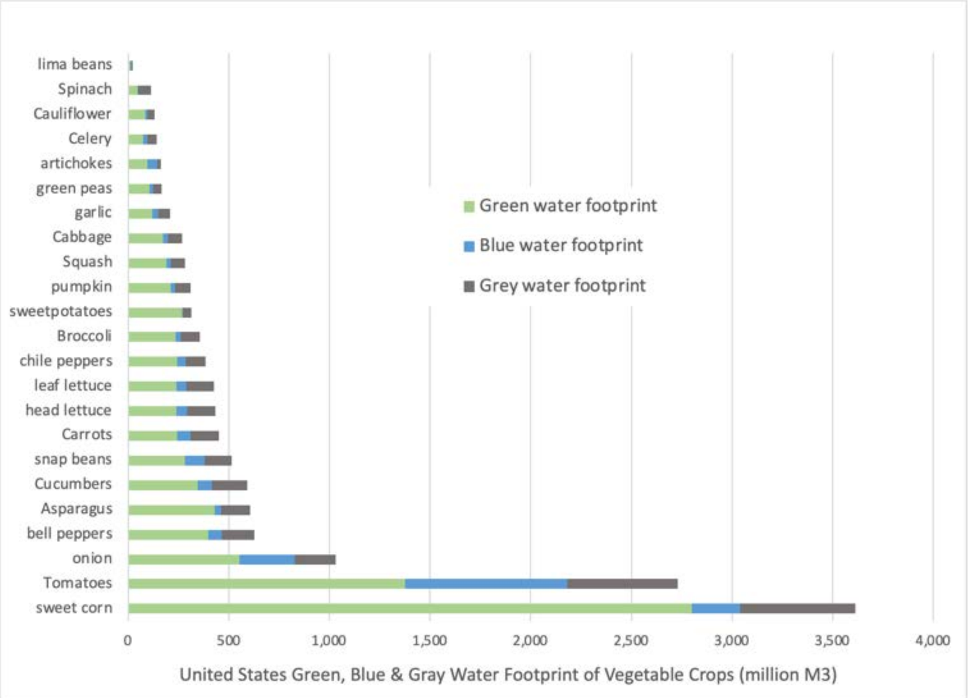
CEA cultivation reduces water pollution by reducing total fertilizer & pesticide use & has the potential for recycling of nutrients from wastewater

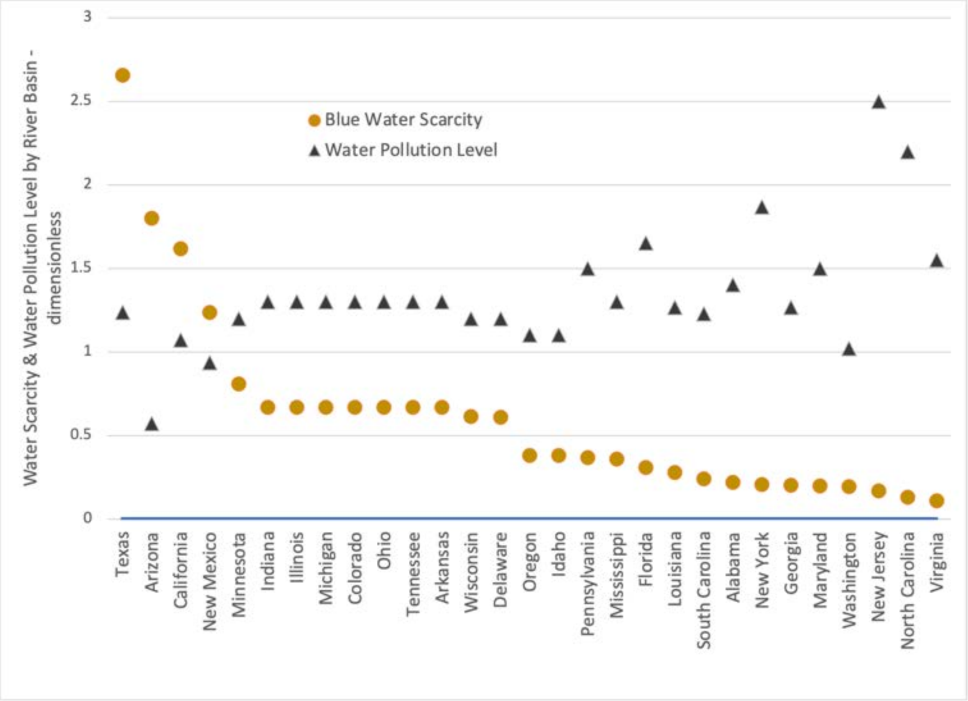
Million m^3

- Blue water footprint (irrigation); volume of surface and groundwater consumed (evaporated) as a result of the production of a good
- Green water footprint; natural precipitation
- Grey water footprint; the volume of freshwater that is required to assimilate the load of pollutants based on existing local water quality standards. Only applies to nitrogen fertilizer for the referenced study

Dimensionless

- Blue Water Scarcity; water demand fraction of water supply





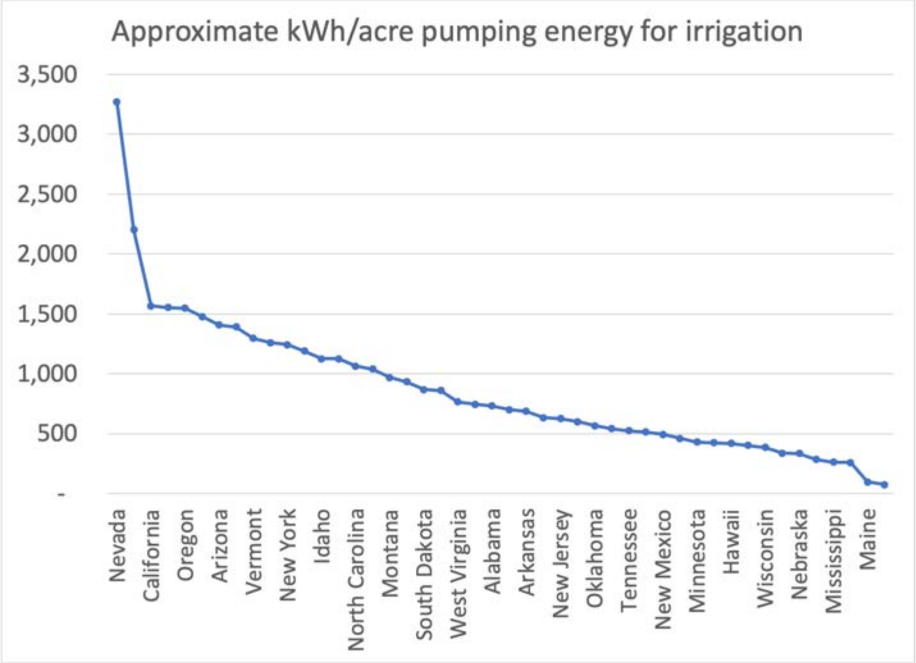
Source: Mekonnen, M. M., and A. Y. Hoekstra. "The Green, Blue and Grey Water Footprint of Crops and Derived Crop Products." Hydrology and Earth System Sciences 15, no. 5 (May 25, 2011): 1577–1600.

Energy & Water Relationships

Transitioning vegetable production to CEA plant factories would save ~780 GWh of irrigation energy/year

Crop - Location	Energy Use (MJ/m³)[2]	Water Use (L/cap/yr)	Energy Use for Water (kWh/cap/yr)
field	0.63[1]	9,200	2.9
CE Farm (urban)	2.71 (water supply) 2.05 (wastewater treatment)	360	0.5

In 2012, 74 percent of vegetables acres harvested were irrigated (Canning et al. 2020)



- Water transport and delivery takes more energy
- Pumping energy/acre varies over almost two orders of magnitude depending on;
  - Well depth
  - Transport distance
  - Acre-feet applied per acre

1. Equivalent pumping energy for 38.5 m (~125 ft) head (engineering toolbox https://www.engineeringtoolbox.com/pumps-power-d_505.html), some estimates are up to an order of magnitude higher
2. Mohareb et al., 2017

Key Takeaways

Understanding and accounting for the impacts of location is a key component of sustainability metrics for vegetable production in conventional agriculture and CEA plant factories

- Nationwide, vegetable crop irrigation accounted for only ~2% of freshwater withdrawals, but those withdrawals occur in water-stressed regions.
- Transitioning PF vegetable production to CEA plant factories would save ~3 BM^3 of irrigation water and 780 GWh of pumping energy per year.

Thank You

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NREL Transforming ENERGY

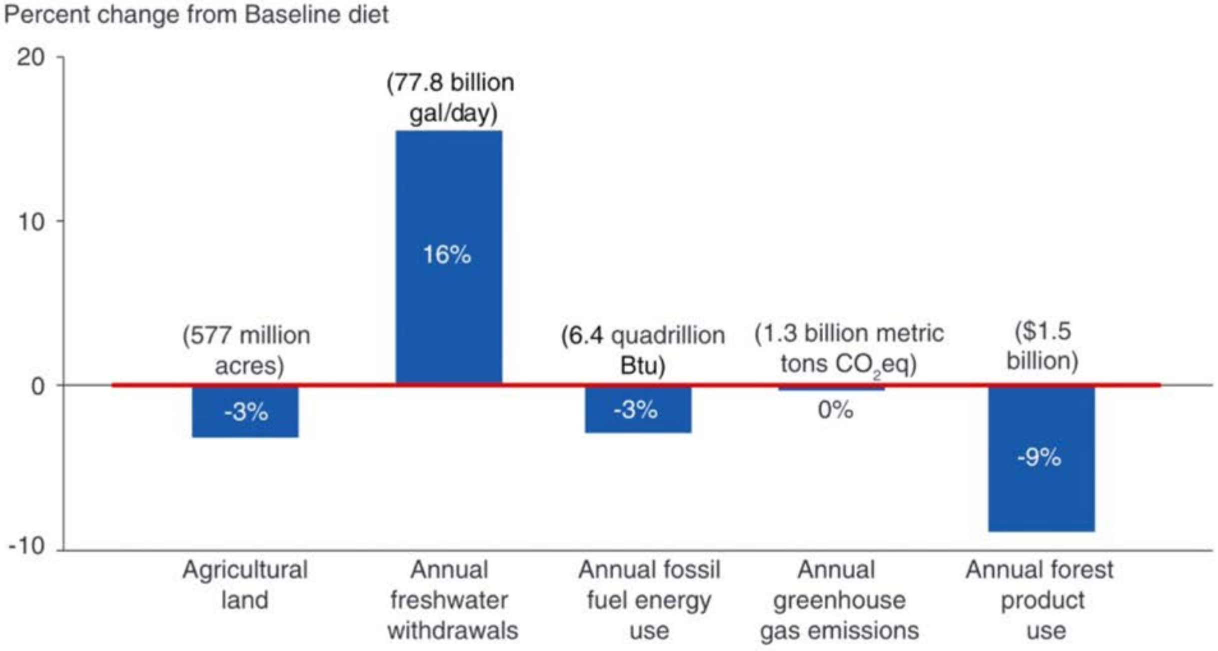
Americans would have to double their consumption of fruits and vegetables to transition to a healthy American diet (HAD)

U.S. Department of Health and Human Services and U.S. Department of Agriculture 2015

Transitioning to the HAD would reduce resource use in all categories except freshwater withdrawals

Canning et al. 2020

Estimated percent change in resource use going from Baseline to Healthy American diet



Btu = British thermal units. Note: Baseline diet is measured from the 2007–08 National Health and Nutrition Examination Survey (NHANES) (USDHHS CDC NCHS, 2013a)—a nationally representative survey of food intake by all Americans ages 2 and above. All diets are linked to the annual 2007 U.S. personal consumption expenditures on food (BEA, 2015). Healthy American diet is from a model that estimates the most likely food intake by all Americans in the 2007–08 NHANES sample who are meeting all 2010 *Dietary Guidelines for Americans* (USDA and USDHHS, 2010).

Source: USDA, Economic Research Service.

Source; Canning et al. 2020

Current ➢ HAD **reductions** in calories

- Sugars, sweets, & beverages -67%,
- Fats & oils -94%,
- Meats -24%,
- Grain products -9%

Current ➢ HAD **increases** in calories

- Legumes & nuts +173%,
- Fruits +101%
- Vegetables +107%
- Dairy +63%