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Evaluating tomato production in open-field and high-tech greenhouse systems

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ABSTRACT

High-tech greenhouse production of vegetables has been proposed as a path to sustainable intensification of food production. While these systems have clear productivity advantages, there are outstanding questions around their overall sustainability that merit evaluation. Using a simulation approach, we assessed crop yields, water, energy, and greenhouse gas footprints, average cost per unit of tomato produced, and net income for Washington State, United States as a case study. Compared to open-field production, high-tech greenhouse resulted in 6.4 times yield per unit area with 231 times energy, 18 times greenhouse gas, and 0.74 times water footprints (per unit of fresh tomato mass). Greenhouse tomato cultivation would need to focus on both reducing the energy needs and shifting to cleaner sources to reduce environmental impacts and lead to sustainable intensification of food production.

1. Introduction

High-tech greenhouse (HiTechGH) systems have been proposed as a means to sustainable intensification of food production. Originally developed in the Netherlands, HiTechGH systems offer control of indoor climate to achieve optimal temperature, supplementary illumination, thermal screens to protect against excessive incident radiation, carbon dioxide (CO_2) fertilization, and humidity control. Despite the barrier of large upfront investment costs (Laate, 2018; Tasgal, 2019), the controlled environment provides several advantages: increased productivity (Kozai et al., 2016; Ntinas et al., 2017), ability to extend the duration of the growing season (Cook and Calvin, 2005), production in regions with unfavorable weather and soil conditions, logistical ability to provide consistent quality and supply that is appropriately spaced out over time (Baskins et al., 2019), and small land use and on-site water footprint (Ntinas et al., 2017; Payen et al., 2015). Additional benefits related to greenhouse (GH) sustainability include the ability to reuse the excess heat produced by data server centers (Ljungqvist et al., 2021) and removal (Koytsoumpa et al., 2018) and reuse (Marchi et al., 2018) of CO_2 from exhaust emissions of fuel-fired power plants (Kim et al., 2020).

Food and energy production rely heavily on scarce water and land resources (D'Odorico et al., 2018), and there is no doubt that HiTechGH production facilitates intensive agriculture – producing more food with less on-site water and land inputs than open field (OF) agriculture (Ntinas et al., 2017, 2020). However, unintended consequences include higher greenhouse gas (GHG) emissions (Irabien and Darton, 2016) and intensive energy use (Vadiee and Martin, 2014). Given the widespread recognition that agricultural intensification to meet the food demand by 2050 (Tilman et al., 2011) needs to be sustainable (Pretty and Bharucha, 2018) – conducted in a manner that minimizes irreversible negative impacts on resources and the environment (Foley et al., 2011) – it is critical to evaluate outstanding questions around the overall sustainability, resource use, and environmental impacts for HiTechGH and OF production systems.

Existing literature evaluating HiTechGH production systems is limited and has primarily focused on European (e.g. Ntinas et al., 2020, 2017; Pérez Neira et al., 2018; Torrellas et al., 2012; Payen et al., 2015) and Australian (Page et al., 2012) production systems. Additionally, limited existing work (Boulard et al., 2011; Ntinas et al., 2017, 2020) takes a holistic approach of including direct (onsite) and indirect (offsite) environmental footprints. There is a wide variation of results depending on whether indirect footprints are included, type of technology used, site-specific climatic conditions, characteristics of energy sources, and system boundary assessed. Given the increasing trend of HiTechGH productions systems in North America (Baskins et al., 2019), our objective is to evaluate HiTechGH production systems and compare them with OF production in this region. Using tomato production in Washington State in the Pacific Northwest United States (US) as a case

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study, we take a simulation approach and evaluate both direct (onsite) and indirect (offsite) water, energy, and greenhouse gas footprints, and economics of HiTechGH and OF production.

We focus on tomatoes for two reasons. First, commercial GH systems have had demonstrated success with growing tomatoes. Second, per-capita availability of fresh tomatoes in the US increased from 12 pounds in the early 1980s to upwards of 20 pounds in recent years (Baskins et al., 2019), in part due to increased adoption of GH technologies although other aspects such as changing consumer preferences, demographics, and increased imports have also shaped the demand and supply for fresh tomatoes (Tilman and Clark, 2014). While California and Florida continue to lead in US open-field tomato production, in recent years significant tomato production has been introduced in other parts of the US that are not traditional market leaders – for example, Nebraska, Minnesota, and New York (USDA, 2014) – through the introduction of GH systems, and the trend may continue.

Washington State (WA) is a good case study region for multiple reasons. First, California (CA) –the lead in vegetable production in the US– is being impacted by a long-term decline in water supply, reduction of snowpacks, increase of temperature, and higher frequency of heat waves and droughts. Groundwater in CA has reached historic low levels and ongoing droughts have led to increased scarcity of surface water supplies (Howitt et al., 2014). Furthermore, the increase in air temperature also affects the production of crops, especially tomatoes, that are typically grown under milder temperatures. Therefore, current levels of vegetable production in CA may be unsustainable in the coming decades (Pathak et al., 2018; Kerr et al., 2018), and some production might be displaced to other favorable regions in the US. Second, the Columbia River basin –part of which is in WA - is the fourth largest watershed in North America (OCR, 2016), and provides abundant water, which is intensively managed to meet a range of competing demands (irrigation, fish, hydroelectricity, recreation), with irrigation accounting for about 79.4% of the total out-of-stream water withdrawals (OCR, 2016). Extensive irrigation infrastructure supports secure water access and rights (Rajagopalan et al., 2018) to over 250 commercial crops including fruit trees, berries, vegetable crops, and grains (USDA, 2014; Yorgey et al., 2017). Although minimal OF tomato production currently exists in WA and HiTechGH production is nonexistent, production challenges in CA (Pathak et al., 2018), access to cheaper and cleaner hydropower energy (Markoff and Cullen, 2008), and relatively more secure water supply create opportunities for potential introduction of both HiTechGH and OF tomato production in WA.

2. Methodology

The HiTechGH and OF production of fresh tomatoes was evaluated using dynamic simulation models to determine yield, water, energy, and GHG footprints, production cost and net income. For HiTechGH production, we selected three locations in WA with contrasting climatic regimes: Puyallup (West), Pasco (Central), and Spokane (East), located near cities with urban infrastructure and access to labor (Fig. 1). The OF production was evaluated in Pasco where irrigation supply is available and favorable growth conditions of irradiance and temperature exist.

2.1. Weather data

We used hourly meteorological data from the Washington State University Agricultural Weather Network (AgWeatherNet, 2014) database (Table 1). Missing data was imputed using the functions of the "zoo" library in R (Zeileis and Grothendieck, 2014). All results were reported for the period 2009 to 2018 where data was available in all locations.

2.2. Open-field tomato production

For OF production of fresh tomatoes, we used the daily time-step CropSyst model (Stöckle et al., 1994, 2003, 2014) to simulate crop yield (assumed as marketable yield) and irrigation water demand (drip irrigation) in Pasco, WA. A planting date of March 1st was used for each season. Harvest occurred at the accumulation of 1,034 growing degree days (°C-days) using a base temperature of 10 °C (Altes-Buch et al., 2019). Soil data was obtained from the State Soil Geographic Database (STATSGO) developed for the U.S. Department of Agriculture, Natural Resources Conservation Service (USDA-NRCS, 2006). The predominant sandy soil series in Pasco was used.

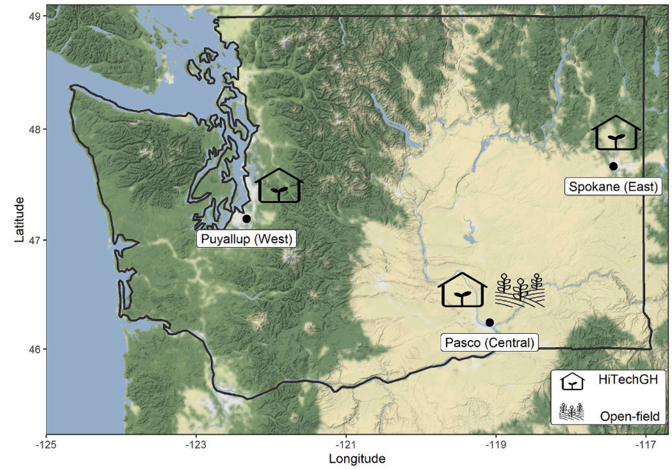


Fig. 1. Location of the three sites for High-tech greenhouse (HiTechGH) and open-field (OF) fresh tomato production with appropriate symbols. The Washington State border is shown in black.

2.3. Greenhouse tomato production

An open-source dynamic modeling library developed in the Modelica language (Fritzson and Engelson, 1998) for HiTechGH in the Netherlands was used to simulate tomato crop yield (assumed as marketable yield; Bosona and Gebresenbet, 2018), energy and water use. The HiTechGH Modelica Library (Altes-Buch et al., 2019) provides a modeling framework for simulating energy flows of controlled indoor climate, tomato growth, and energy use relative to the coupling of various components in HiTechGH systems (Altes-Buch et al., 2019).

HiTechGH tomatoes are transplanted once a year and grown for 9–10 months (UGA extension, 2017). We evaluated tomatoes transplanted on March 1st and grown until November 30th of each year, with a plant density of 3.5 plants m^{-2} and continued auto-pruning to maintain a leaf area index (LAI) of 2.7 m^2 m^{-2} (Altes-Buch et al., 2019; Vanthoor et al., 2011b). Irrigation was always available, and water did not limit the growth of tomatoes. We assumed a drip irrigation system that also provides nutrients, with the water taken up by roots and evaporated through plant stomata recuperated and recirculated. We also accounted for the loss of water due to exchange of outdoor and indoor water vapor via the opening of the roof ventilation, which also facilitates indoor temperature control. We assumed a non-reactive substrate such as a slab/bag filled with coconut fiber to provide support and air to the root system (Hochmuth and Hochmuth, 2012).

2.3.1. Greenhouse system description

A Venlo type HiTechGH – a type of glasshouse with a design that optimizes space usage and is a convenient design for covering large areas (Magan et al., 2011) – was simulated (Fig. 2). The HiTechGH system covers an area of 1 ha, with roof ventilation, supplementary lighting, thermal screens, heating cells, and CO_2 fertilization. The HiTechGH is powered and heated with combined heat and power (CHP) using natural gas and electricity from the grid. A thermal 313 m^3 tank is used to store heat. The amount of energy and mass required by each

Table 1
Description of the weather stations used.

Site	Station name	Years covered/simulated	Mean average temperature (°C)	Mean minimum and maximum temperature (°C)	Annual precipitation (mm)
West	Puyallup	2009–2018	10.8	−7.8 – 32.7	1004
Central	Pasco	2009–2018	13.5	−11.2 – 37.7	118
East	Davenport	2009–2018	10.4	−13.7 – 35.1	140

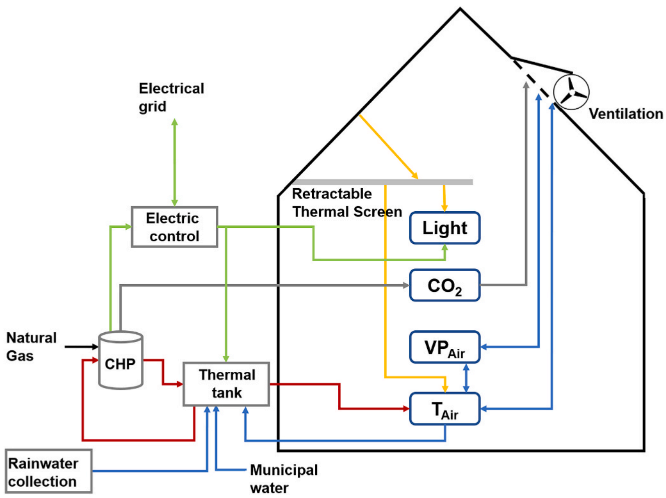


Fig. 2. Schematic of the HiTechGH components. Connection of flow of electricity (green line), heated water (red line), cold water (blue line), carbon dioxide (CO_2, grey line), natural gas (black line) and solar radiation (orange) are shown. Other variables include vapor pression (VP_{Air}), temperature (T_{Air}), and combined heat power (CHP).

design element to operate the system were based on Vanthoor et al. (2011b) and Altes-Buch et al. (2019). We used an hourly control design for illumination, thermal screens, desired indoor temperature, and CO_2 fertilization, and included outside solar irradiation, air temperature, relative humidity, and wind speed.

Lighting control: The lighting control was active from 5 a.m. to 10 p.m. Lights were turned on if the incident solar radiation was below 40 W m^{-2} and turned off when above 120 W m^{-2}. To ensure an adequate bulb life a minimum of 2 continuous hours of illumination time was ensured per cycle.

CO_2 fertilization control: Elevating daytime HiTechGH carbon dioxide (CO_2) concentration increases photosynthesis rates resulting in a larger biomass production and shorter production time (Poudel and Dunn, 2017); however, maintaining a high internal CO_2 concentration (~1000 ppm) might increase operational costs (Bailey and Hayman, 2002). Given that our combined heat and power system was powered by natural gas fuel, CO_2 was recuperated from the exhaust gases and used to enhance CO_2 fertilization, thus lowering operating costs as compared to procuring CO_2 from an outside source. Since CO_2 uptake only occurs when light is present, its concentration was set at 1200 ppm during the day and reduced to 500 ppm at night. we did not consider the cost of purifying the CO_2 from other gases.

Thermal screen control: The HiTechGH was simulated with a retractable aluminum thermal screen. The thermal screen was retracted when artificial illumination was activated and extended when illumination was deactivated. Extension of the thermal screen reduces incident solar radiation on tomato fruits, preventing loss due to quality defects. The thermal screen also helps maintain stable indoor temperature by (a) functioning as a thermal isolator from lower nighttime outdoor temperatures and (b) providing shade and reflecting incident radiation during the day to protect the tomatoes plant from high intensity solar radiation.

Indoor temperature control: The system has an indoor temperature control aperture for roof ventilation and heating cells regulated via Eq. (1). The desired hourly indoor temperature was adjusted using the algorithm presented in Eq. (1) to meet the optimal night (16–22 °C) and day (26.6–29.4 °C) time temperatures (Hochmuth and Hochmuth, 2012). In this equation, S_r corresponds to solar radiation (W m^{-2}), *ws* corresponds to wind speed (m s^{-1}), *RH* corresponds to relative humidity (percentage), T_{sky} corresponds to sky temperature (°C; Campbell and Norman, 1998), *LC* corresponds to illumination activated (0/1), and CO_2 corresponds to CO_2 concentration (ppm).

$$T_{indoor}(^{\circ}C) = 0.0091\ S_r + 0.0103\ ws + 0.0054\ RH - 0.0116\ T_{sky} + 0.3767\ LC - 0.0001\ CO_2 + 14.95 \quad \text{Eq. 1}$$

2.3.2. *Energy source*

The combined heat and power (CHP) unit generates electricity, heat, and CO_2. The CHP can operate on full-load and does not allow a partial-load operation (Altes-Buch et al., 2019). In a typical control, CO_2 fertilization is applied during the day when electricity and heat are produced. A thermal tank allows for heat to be stored for later use, and electricity can be bought from the grid if necessary.

Two sources of energy were used: natural gas (Gas CHP) and electricity from the grid (Elect. Buy). The energy generated from the CHP unit was partitioned into electricity (Elect. CHP), thermal (Thermal CHP), and energy loss (CHP thermal loss) components. A part of the electricity from the grid was used in the heat pump (HP) to heat up the water used in the CHP unit (Elect. HP). The HP recuperates part of the heat from the CHP and recirculates heat (Thermal HP) back to the CHP unit. The total thermal energy generated (Thermal total) was stored in the thermal tank and then used in the HiTechGH. The thermal tank uses part of the electricity to maintain the water temperature (Elec. TES). When the CHP unit was unable to meet the instant demand for electricity from devices in the HiTechGH, the energy deficit was met from the electrical grid. Under high incoming radiation, illumination is turned off. Consequently, part of the energy generated was diverted as surplus of energy (Elect. Sell). The electricity used (Elec. GH) and the heat used (Thermal GH) in the HiTechGH were reported as Energy GH. We assumed that the electric grid network would absorb the surplus energy.

2.4. *Comparison of performance of greenhouse and open-field cultivation*

We evaluated the performance of HiTechGH and OF tomato production based on inputs (Davis et al., 2016) and outputs per unit of fresh mass (6% dry matter content in fruit) and unit area. Categories of variables evaluated are described below. Where appropriate, the variable is split into direct (onsite) and indirect (offsite) components.

Energy-use: The total energy includes fossil fuel (E_{Fossil}) and grid electricity (E_{Grid}) components (Eq. (2)). In HiTechGH, the total energy used included natural gas fuel and the net electricity (energy purchased – energy surplus). In OF, the use of fuel and electricity for farm operations such as tillage, irrigation, agrochemical applications, and harvest were included (Klein et al., 2018; NASS, 2011).

$$E_{Total} = E_{Fossil} + E_{Grid} \quad \text{Eq. 2}$$

The study omitted energy used for delivering water on-site (either groundwater or surface water), transportation of products, and for fabrication and extraction of materials like agrochemicals, plastic, and cardboard to produce the final marketable product.

Water-use: We considered direct and indirect components of water use (Eq. (3)). Direct water use includes the annual evapotranspiration rate in OF, water loss in the greenhouse, and water exported in the fruit (Eq. (4)). Indirect water use is the water consumption associated with offsite energy generation (Eq. (5)).

The indirect water footprint is quantified by multiplying the grid energy produced offsite by an average water use conversion factor. The electricity grid (U.S. Department of Energy, 2016) in WA has multiple sources partitioned as hydropower (76.6%), natural gas (4.6%), non-hydroelectric renewables including solar and wind power (5.7%), nuclear (8%), and coal fired (3.3%), each having a specific conversion factor (see supplementary materials SM1 for details). The integrated consumptive water footprint in WA (F^{W}_{Grid}) is 0.61 L per kWh of electrical energy sourced from the grid, and the average conversion factor of fossil fuel (F^{W}_{Fossil}) is 0.46 l kWh^{-1}. Details of these estimates are in the supplementary materials section SM 1.

$$W = W_{Direct} + W_{Indirect} \qquad \text{Eq. 3}$$

$$W_{direct} = \begin{cases} ET + W_{Exported}, & \text{if } OF \\ W_{loss} + W_{Exported}, & \text{if } HiTechGH \end{cases} \qquad \text{Eq. 4}$$

$$W_{Indirect} = E_{Fossil}\, F^{W}_{Fossil} + E_{Grid}\, F^{W}_{Grid} \qquad \text{Eq. 5}$$

GHG: Total GHG footprint includes direct (onsite) and indirect (offsite) components (Eq. (6)). Direct GHG includes that derived from the fossil fuel used onsite and the emissions from OF tomato production (Eq. (7)). For HiTechGH, CO_2 emissions were calculated from energy used in the CHP unit using the conversion factor (F^{GHG}_{Fossil}) per kWh burned from natural gas (0.18 kg CO_2 kWh^{-1}; EPA, 2020). The OF's $Prod^{GHG}_{System}$ was determined using the IPCC (Intergovernmental Panel on Climate Change) tier I and II methodology (Buendia et al., 2019; Eggelston et al., 2006), which includes emission of nitrous oxide (N_2O) as a CO_2 equivalent (CO_2-eq). N_2O emissions in OF are driven by the amount of nitrogen applied. In addition, fuel used in OF production was converted to CO_2 and added to GHG_{OF}. The HiTechGH $Prod^{GHG}_{System}$ emission from fertilized tomato beds in the greenhouse was determined using 0.04 $kgCO_2\ kg^{-1}$ emission factor and the tomato yield (Page et al., 2012). The Indirect GHG was based on electricity bought from the grid converted to CO_2 equivalent (Eq. (8)), using a conversion factor (F^{GHG}_{Grid}) of 0.00989 $kgCO_2\ kWh^{-1}$ and fossil fuel energy supply with a conversion factor (F^{GHG}_{Supply}) of 8.4 10^{-7} $kgCO_2\ kWh^{-1}$. The details of the GHG conversion factors for each energy source are in the supplementary materials SM 2.

$$GHG = GHG_{Direct} + GHG_{Indirect} \qquad \text{Eq. 6}$$

$$GHG_{Direct} = E_{Fossil}\, F^{GHG}_{Fossil} + Prod^{GHG}_{System} \qquad \text{Eq. 7}$$

$$GHG_{Indirect} = E_{Grid}\, F^{GHG}_{Grid} + E_{Fossil} F^{GHG}_{Supply} \qquad \text{Eq. 8}$$

Production cost: We consider the direct cost of production per unit of fresh tomato (Eq. (9)). All dollars were adjusted to 2018 levels. Farm operations, material use, and agrochemical costs were considered. Fertilization and chemical application rates were obtained from annual surveys for fresh market production in California (NASS, 2011), if similar rates apply in WA. Operation and material costs were obtained from University of Delaware Cooperative Extension Vegetable (Ernest and Johnson, 2017). For HiTechGH, the main operations and material costs were obtained from statistics from Alberta, Canada (Laate, 2018). The cost of wage labor, electricity, and natural gas was adjusted to WA historical prices. The yearly price of industrial electric energy and natural gas were obtained from the US Energy Information Administration (U.S. Energy Information Administration, 2020), and the WA wage for labor was obtained from the WA State Department of Labor and Industries public database (LNI, 2020). The land cost was considered as a lease price. For HiTechGH, the assumed lease prices were based on marijuana production in the region. The investment costs of HiTechGH were obtained from Laate (2018) and the OF investment from (Klein et al., 2018). Investments were included in the variable cost calculation as depreciation. Investment items include all machinery and equipment, and in the case of HiTechGH, the building structure. The repair costs were calculated as a percentage of the list price of the machine and equipment (Mohamed Kheir, 2010). Depreciation and repairs for the HiTechGH structure was determined using a life of 24 years for HiTechGH and the expected life for the machinery and equipment for OF. Details of cost and investment for HiTechGH and OF are in supplementary material SM3.

$$Cost_{Direct} = \sum_i Material_i\ Price^{Material}_i + \sum Labor\ Wage_{year} + \sum_i E_i\ Price^{E}_{year} + \sum Land_{rent} + \sum Marketing + \sum Depreciation + \sum Repairs + \sum Miscelaneous \qquad \text{Eq. 9}$$

Economic benefits: We consider the net income (Dhaliwal et al., 1999) of tomato production excluding income from the transfer of surplus energy to the grid (Eq. (10)). We used the annual farm gate price ($Price^{Tomato}$) reported by the Economic Research Service (USDA-ERS, 2019). Usually, the price of fresh tomatoes grown in controlled environments is about 10 cents higher than that of (Baskins et al., 2019), but this fact was neglected from our analysis since a time series data of this effect was not available. We assumed that the production of fresh tomatoes grown in GH would not affect the price for fresh tomatoes in the US market because growers are "price takers" (Adam and Adcock, 2005; Moss et al., 2003), and a single producer does not have the power to control the market price.

$$Net\ Income = Yield\ Price^{Tomato} - Cost_{Direct} \qquad \text{Eq. 10}$$

WA has implemented net metering (Darghouth et al., 2016) for projects up to 100 kW where utility companies provide a credit for surplus energy at the same price charged for electricity supply (80.60RCW, 2019). However, net metering is limited only to renewable sources of energy. Given we used natural gas – which is excluded from the net metering benefits – in the CHP unit, we exclude any revenue for a surplus of energy in our analysis.

3. Results

The summary of footprints and production cost per kg of fresh tomato produced, and net income is presented in Table 2.

3.1. Fresh tomato production and water footprint

Simulated tomato yields per unit area in HiTechGH are 6.4 times that of (Fig. 3a). We observed some differences in yield, with the West and East sites having higher yield than the Central site. The lower average

Table 2
Summary of footprints, production cost and net income for the open-field (OF), and HiTechGH simulation sites. The production cost and net income were inflation-adjusted to 2018.

Category	OF	West	Central	East
Tomato yield kg m^{-2}	10.6 ± 1.3	71.4 ± 2.7	60.2 ± 10.7	71.6 ± 2.7
Water footprint L kg^{-1}	46.6 ± 6	31.6 ± 4	34.1 ± 10.3	37.8 ± 5.8
Energy footprint MJ kg^{-1}	0.05 ± 0.01	12.51 ± 0.57	10.96 ± 1.87	11.13 ± 1.14
GHG footprint kg CO2 eq. kg^{-1}	0.05 ± 0.002	0.88 ± 0.01	0.86 ± 0.06	0.96 ± 0.05
Production cost $ kg-1	$0.06 ± 0.01	$0.91 ± 0.06	$1.06 ± 0.2	$0.9 ± 0.06
Net income $ m^{-2}	16.1 ± 3.6	$46.8 ± 19.4	$34.5 ± 30.6	$41.4 ± 15

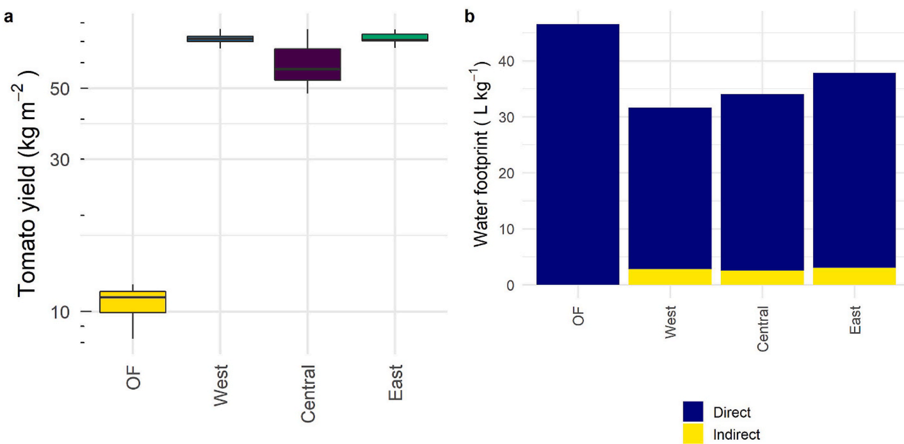


Fig. 3. a) Fresh tomato yields for HiTechGH at three locations, and for OF yields at Central WA., b) Water footprint in liters (L) per unit of fresh tomato produced.

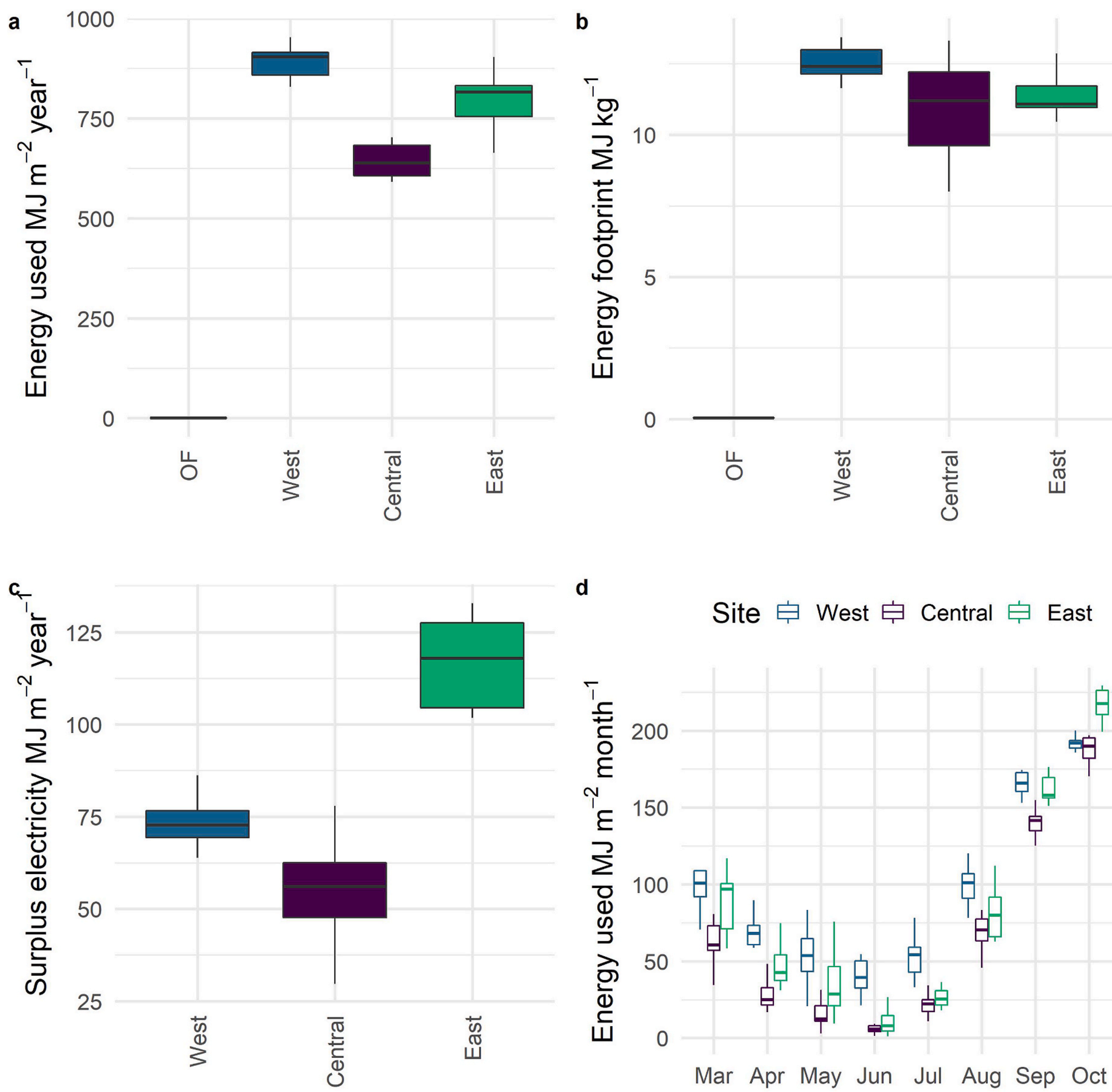


Fig. 4. (a) Energy used (total energy minus surplus electricity) in the production of tomatoes in HiTechGH and OF. (b) Energy footprint per unit of kg of fresh tomato produced. (c) Surplus of HiTechGH generated electricity sent to the grid. (d) monthly total energy.

yields, and higher variability in the Central site, can be explained by frequent episodes of elevated temperatures of fluctuating intensity. The forced roof ventilation was unable to fully dissipate the heat resulting in higher plant heat stress compared to the other sites.

HiTechGH water footprint per unit mass of fresh tomato was 0.74 times that of (Fig. 3b), and primarily comprised of the direct component related to plant transpiration. Our indirect water footprint contributes 7.4%–8.9% of the total water footprint, a low value explained by the use of a 76% hydropower energy-source (U.S. Department of Energy, 2016) without consumptive water use.

3.2. Energy

The total energy use, energy footprint, surplus electricity and monthly energy used in HiTechGH and OF production systems are shown in Fig. 4. The energy used after discounting the surplus electricity is shown in Fig. 4a and b provides the footprint on a per unit mass basis. The HiTechGH energy use was 231 times that of the OF system. Higher energy use observed in the West and East sites was due to higher heater energy needs in these two sites. However, energy intensity for HiTechGH was about the same for all sites with a greater variability in the Central site given its higher variability in yields. The highest amount of energy surplus was in the East site and the lowest in Central site (Fig. 4c). Under variable incoming radiation, illumination is turned off and on, resulting in a higher surplus energy than East and West sites. The energy use in the HiTechGH is lower during the summer months and increases during the fall season (Fig. 4d), given the higher heating requirements.

The share of total energy (natural gas and electrical grid) used in the HiTechGH across subcomponents is shown in Fig. 5. In the HiTechGH, the energy used for all operations to produce tomato was 89.9–95.8% of the total energy used (Energy GH in Fig. 5). Electricity purchased from the grid was a much larger contribution than from the CHP because illumination was the largest factor (Table 3), and the CHP unit was mainly used for heating. The surplus energy was 5.7–12.4%, and the energy lost from the CHP unit was 1.8–4% of the total energy used. The energy purchased from the electrical grid was used almost exclusively for the lighting system given that the CHP was frequently used to heat the HiTechGH at night. When we analyzed the daily evolution of energy used, the largest use of energy was registered in the early hours (5–7 AM) to activate the system after maintaining an optimal night temperature (16–22 °C), which required initiation of illumination and heat to reach the optimal day-time temperature (26.6–29.4 °C) (Hochmuth and Hochmuth, 2012). The East site had similar energy use in electricity as the Central site, but the coldest temperatures in the East site also drove more intense use of the heater compared to the other two sites. The West site used more electricity in illumination than all the other sites because cloudy conditions were more frequent.

Table 3
Onsite HiTechGH energy use partitioned into heat and illumination components.

Site	Heat (%)	Illumination (%)
Central	19	81
East	32.7	67.3
West	18.9	81.1

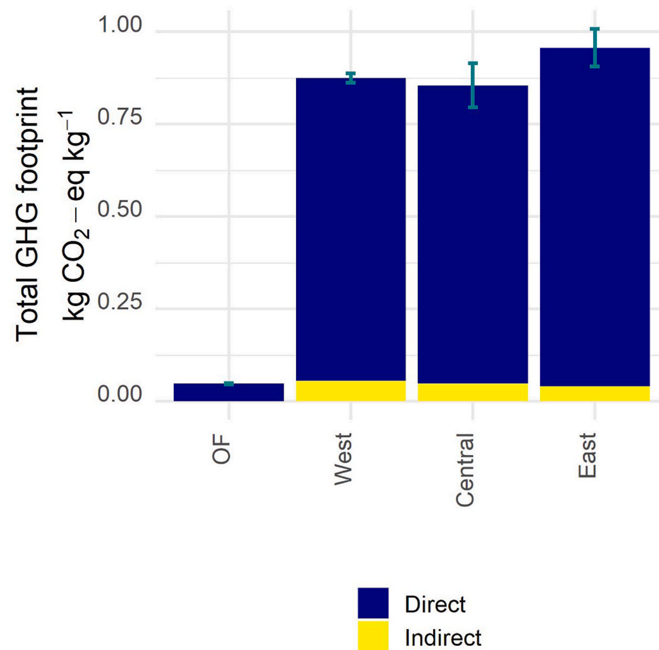
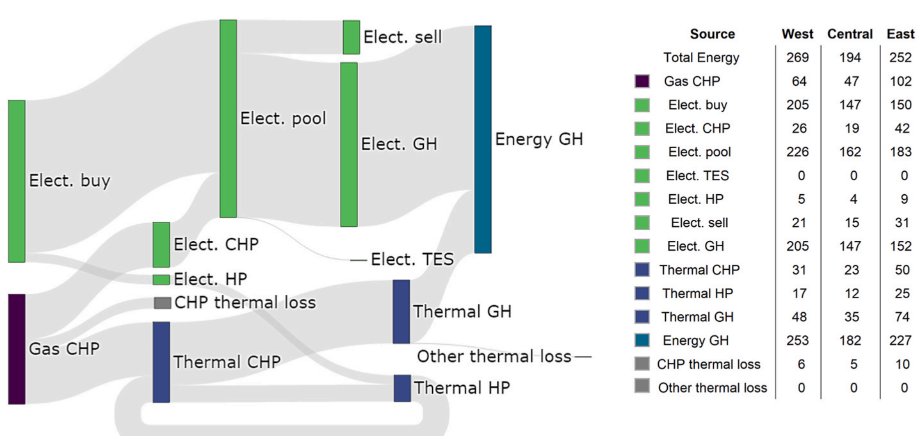


Fig. 6. Greenhouse gas (GHG) emissions footprint per kg of fresh tomatoes in OF and HiTechGH cultivation. For OF, the GHG includes CO_2 and CO_2 equivalent of N_2O emission.

3.3. Greenhouse gas emission

The GHG footprint in HiTechGH was 18 times that of OF system (Fig. 6). The direct GHG footprint was responsible of a large portion (75%–88%) of the total GHG footprint. A large portion of the CHP was used in heat production, which is consistent with previous literature that identified heat requirement as key to reduce environmental impacts (Page et al., 2012).



Source	West	Central	East
Total Energy	269	194	252
Gas CHP	64	47	102
Elect. buy	205	147	150
Elect. CHP	26	19	42
Elect. pool	226	162	183
Elect. TES	0	0	0
Elect. HP	5	4	9
Elect. sell	21	15	31
Elect. GH	205	147	152
Thermal CHP	31	23	50
Thermal HP	17	12	25
Thermal GH	48	35	74
Energy GH	253	182	227
CHP thermal loss	6	5	10
Other thermal loss	0	0	0

Fig. 5. Annual flow (left to right direction) of energy (MJ m^{-2}) in the HiTechGH system for West, Central and East sites by source (diagram shows East site flows).

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3.4. Production cost and net income

A large portion of the OF production cost was from materials used whereas for HiTechGH it was marketing, followed by labor and electricity costs. The investment cost which includes equipment and land for HiTechGH ($91.87 m^{-2}) was 1.8 times that of OF ($51.47 m^{-2}). The average annual net income is shown in Fig. 7.

4. Discussion

This study provides novel information on commercial tomato production in HiTechGH and OF systems, with a focus on Washington State as study case. In this section we compare the results of our study with other studies, and we analyze productivity, environmental impact, and economics of the two systems.

Tables 4 and 5 provide comparisons of results from our study and

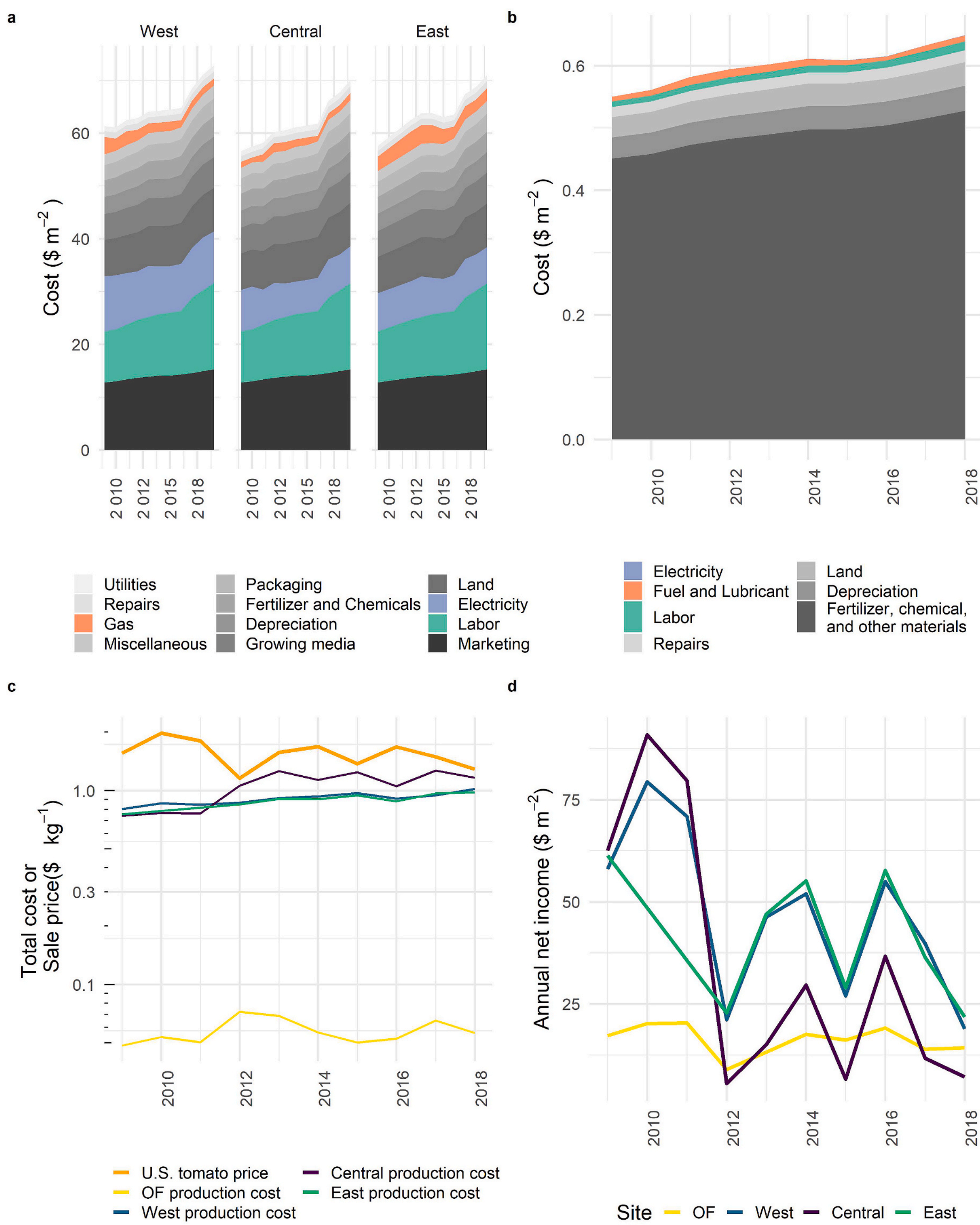

Fig. 7. Time series of the cost of producing tomatoes in (a) HiTechGH and (b) OF. For these panels, the grey color scale indicates a value adjusted only for inflation, price in color (green, orange, and blue) was updated for the inflation and the annual quantity used. Panel (c) is the production cost per unit of tomato along with the historical annual price received by farmers (dark green line), and (d) is the net income (sales revenue – total cost).

Table 4
Review of open field (OF) production of tomatoes. Headers: Tomato yield in kg m^{-2} (Yield), Water footprint in L kg^{-1} (W), Energy footprint in MJ kg^{-1} (E), Greenhouse gas footprint in kg CO2 eq. kg^{-1} (GHG), T: Temperature, P: Precipitation, and Combined heat power (CHP). Abbreviations: F: Farming, P: Packing, T: Transport to market, S: Structure/Construction, N: No, and Y: Yes. Cells were highlighted in red if the values were lower, blue if the values were higher, and white if the value were in the same range as compared to results from this study (Page et al., 2012; Hartz et al., 2008; Zarei et al., 2019; Ntinas et al., 2017; Karakaya and Özilgen, 2011; Evangelou et al., 2016).

Reference	W	E	GHG	Yield	Study base	Location	Season Length	Avg T (C)	Avg P (mm)	System boundary	Indirect footprint
Page et al., 2012	39	9.55	0.3	6	Simulated	Sydney, Australia	Year around	22	1100-1900	F-P-T	Y
Hartz et al., 2008	-	-	-	11	Reported	California, USA		18.3	292	F	N
Zarei et al., 2019	-	1.2	0.05		Survey	Iran	Aug-Feb	16.8	200	F-S	N
Ntinas et al., 2017	60	6.9	0.5	4	Case study and experimental data	Greece	Apr-Sep	15.4	412	F-S	
Karakaya et al., 2011	30.8	0.76	0.067	9.7	Experimental data	Turkey	-	19	1060	F-T	N
Evangelou et al., 2016	23.4-88.18*	-	-	5.2-19.5	Survey	Greece		15.4	400-1850	F	N
This study	46.6±6	0.05±0.01	0.05±0.002	10.6±1.3	Simulated	WA, USA	March-Sep	13.5	118	F	Y

*Only blue and green water components were considered for comparison

other relevant studies for OF and HiTechGH systems, respectively. In addition to footprint characteristics, other assumptions related to climatic inputs, system components and boundaries are also given for context. Given the high variability in types of GH systems, we restrict Table 5 to HiTechGH systems similar to the one we assessed. We note that direct comparisons are challenging for multiple reasons. First, footprints are reported on a per unit mass basis, and therefore differences in yields translate to differences in footprints as well. Second, the papers make different assumptions about energy sources, conversion factors and vary in system components and boundaries. Sometimes, the specifics of these nuances can be gleaned from papers and other times the information is unclear. Third, some papers are based on simulation exercises and others based on surveys. Lastly, it is unclear if yields reported correspond to total yield produced or marketable yield, the latter reflecting fruit losses that can be high in tomatoes, particularly in open field production. Therefore, this section is intended as a "order-of-magnitude" comparison to make sure our results are in the ballpark of other estimates, and where there is a significant difference in results, make qualitative assessments of the reasons for the discrepancies.

4.1. Open-field (OF) yields and footprints

These comparisons are based on Table 4. The OF fresh tomato yields and water footprint in the present study fall in the middle of the range of values reported in the literature. Variations in weather and management can often lead to differences in yields, and our yield results are close to Hartz et al. (2008) which has the most similar climatic conditions to our simulations. Our energy footprint is lower than other studies which could be partially explained by our smaller system boundary as compared to other work that includes packing and/or transportation as well. For example, Page et al. (2012) with the highest energy footprint notes that 54%–58% of their energy footprints come from post-farming refrigeration, which is excluded from our system boundary. Our GHG footprints are at the lower end of reported values, but consistent with Zarei et al. (2019) and Karakaya and Özilgen (2011). Lower reported yields also partially explain the higher water, energy and GHG footprints reported in Ntinas et al. (2017).

4.2. HiTechGH yields and footprints

The discussion in this section is based on Table 5.

4.2.1. Yields

Many factors make yield comparisons difficult. Some of these factors include differences in GH technology among heated Venlo systems, GH installation (structure quality, computer controls, heating and lighting), management (CO_2 concentration levels, temperature control, growth light intensity and on/off cycles, irrigation and fertilization, pest and diseases control), weather conditions (irradiance, cloudiness, temperature regime), crop growth (plant density, vertical arrangement, season length), and differences in marketable yields (percent fruit loss).

Ntinas et al. (2017, 2020) reported extremely low yields that are not comparable to other studies. Studies based on surveys of producers show yields ranging between 48 and 57 kg m^{-2} (Torrellas et al., 2012; Page et al., 2012), but it is unclear how all the factors previously mentioned impact their results. A simulation study reported yields ranging 50–60 kg m^{-2} (Vanthoor et al., 2011a). Our simulated yields not including fruit losses and based on best management and environmental control are high compared to the studies gathered in Table 5, but not unusual when compared with those obtained in Canadian GH systems in neighboring locations to our study area. For example, higher marketable yields values, were reported in Alberta, Canada (60 kg m^{-2} for top producers, 70 kg m^{-2} for research producers) but the type of GH technology considered was not included (Calpas, 2003) and therefore this reference is not part of Table 5. Adjusting for losses, these reported yields will probably be higher than that estimated in our study. Edwards et al. (2004) also report yields upwards of 70 kg m^{-2} for commercial greenhouses in British Columbia, CA – just north of the border from our study regions in Washington State, US – attributed to exposure to high CO_2 levels, as was also the case in our study.

4.2.2. Footprints

Our HiTechGH total water footprint is in the middle of the range of reported values from previous studies. The lower values correspond to van Kooten et al. (2008) and Torrellas et al. (2012). The values noted in van Kooten et al. (2008) assume a completely closed HiTechGH system with recirculation of water. Our system has a ventilation component that results in a loss of water from the HiTechGH system given the frequent

Table 5
Review of heated Venlo greenhouse system (GH) production of tomatoes. Headers: Tomato yield in kg m^{-2} (Yield), Water footprint in L kg^{-1} (W), Energy footprint in MJ kg^{-1} (E), Greenhouse gas emission intensity in kg CO2 eq. kg^{-1} (GHG), T: Temperature, P: Precipitation, and Combined heat power (CHP). Abbreviations: F: Farming, P: Packing, T: Transport to market, S: Structure/Construction, N: No, and Y: Yes. Cells were highlighted in red if the values were lower, blue if the values were higher, and white if the value were in the same range as compared to results from this study.

Reference	W	E	GHG	Yield	Study base	Location	Season Length	Avg T (C)	Avg P (mm)	Energy source	System boundary	Indirect footprint	Include CHP unit
Vanthoor et al. 2011a	-	-	-	50-60	Simulation	Netherlands	March-Oct	10.2	841	-	F	N	-
van Kooten et al 2008	14-15	-	-	-	Case study	Netherlands	March-Oct	10.2	841	-	F	N	-
Page et al 2012	60	27.42	1.86	57	Case study and Simulation	Australia	Year around	13	150-500	Diesel and grid electricity	F-P-T	Y	Unknown
Torrellas et al. 2012	14.1	12	0.78	56.5	Case study of producers	Netherlands	Year around	10.2	841	Natural gas	F	N	Y
Torrellas et al. 2012	14.6	6.9	0.44	48	Case study of producers	Hungary	49 weeks	9.7	600	Geothermal water	F	N	N
Ntinas et al., 2017	25.6-37	22.2 - 46.1	0.4-0.7	12.1-17.9	Case study and experimental data	Germany	Feb-Nov (281 days)	10.8	675	Heating: Biomass (pellets), Grid electricity	F-S (For GHG only F was included)	Y	N
Ntinas et al. 2020	49.9	53.7	2.5	19.1	Experimental data	Germany	March-Oct	10.8	675	Grid electricity	F-S	Y	No
Boulard et al., 2011	25-31.25	28.2-32.59	1.81-2.1	40-50	Survey	France	Year around	11.6	1050-1290	Non-renewable fossil	F-S-T-P	Y	N
Reference	W	E	GHG	Yield	Study base	Location	Season Length	Avg T (C)	Avg P (mm)	Energy source	System boundary	Indirect footprint	Include CHP unit
										(88%-91%) (Natural gas-90.7%, Oil 4.8%, Coal 2.4% and nuclear (9%-12%)			
This study	31.6±4	12.5±0.57	0.88±0.01	71.4±2.7	West	WA, USA	March-Nov	10.8	1004	Natural gas and grid electricity	F	Y	Y
This study	34.16±10.3	10.96±1.87	0.86±0.06	60.2±10.7	Central	WA, USA	March-Nov	13.5	118	Natural gas and grid electricity	F	Y	Y
This study	37.8±5.8	11.13±1.14	0.96±0.05	71.6±2.7	East	WA, USA	March-Nov	10.4	140	Natural gas and grid electricity	F	Y	Y

trigger of ventilation (26 °C indoor temperature threshold which is exceeded often in our climatic region). Our HiTechGH energy footprints are lower than other literature and GHG footprint are in the middle of the reported range. The higher energy and GHG footprints in other studies can be partially explained by their larger system boundaries and lower yields. Our energy and GHG footprints are close to the results for Netherlands in Torrellas et al. (2012), which is most similar to our study in terms of the system boundary as well as system characteristics such as the use of combined heat and power (CHP) unit. The higher footprints in Ntinas et al. (2020) can be partially explained by the substantially lower yields.

4.3. Economic feasibility

Our OF production cost was \$0.6 m^{-2} - 1% of the average HiTechGH cost (\$63.9 ± 4.1 m^{-2}). Laate (2018) reported similar production costs of \$67.8 m^{-2} US dollars (average Canadian exchange rate of 0.77 for 2018; PSL, 2020) in Alberta, Canada. In the Netherlands, Torrellas et al. (2012) reported a higher cost of \$81.5 m^{-2} (2018 US dollar). For OF tomatoes, a cost of \$1.79 m^{-2} was reported in Delaware including packing boxes; excluding packing boxes, the cost reduced to \$ 0.44 m^{-2} (Ernest and Johnson, 2017), which is lower than the cost found in this study, potentially explained by lower labor wages.

Despite the higher production costs of HiTechGH, both systems for tomato production in WA appear economically feasible. Given its lower and variable yields, the Central HiTechGH site obtained the lowest net income compared to the two cooler sites. Also, central WA is where OF production could become important given the relatively high irrigation water security and favorable weather conditions. This is an important outcome for increasing tomato supply, and partially compensating potential limitations for production in CA, but the potential environmental impact cannot be ignored.

4.4. Scaling up tomato production

HiTechGH system can produce more food with less water than OF systems but with a higher energy and GHG footprint. Given the larger production per unit area in HiTechGH systems, an OF area that is 6.4 times that of the HiTechGH area is required to match total production. This area for equivalent production would result in OF having relative footprints of 0.06 times GHG, 1.4 times water, but still only a fraction (0.004 times) of the energy of HiTechGH. That is, fresh tomato production can scale up either with an intense energy and GHG footprint in HiTechGH or with increased water footprints in an OF system. In addition to the higher water footprint in OF systems, water use related environmental issues such as soil erosion, discharge of chemicals, and fertilizer to aquatic systems are also more likely (Vazirzadeh et al., 2022).

4.5. Approaches to lower the energy footprint of HiTechGH system

Lowering the high energy footprint of HiTechGH systems has an added benefit of lowering the water and GHG footprints as well, given the indirect effects. There are two avenues to lower the negative environmental consequences resulting from HiTechGH crop production: switch to a cleaner energy source or increase HiTechGH's energy efficiency via better design (Ghoulem et al., 2019). Photovoltaic energy sources have been integrated in HiTechGH systems as conventional solar panel fields (Aroca-Delgado et al., 2018) or by replacing glasses for semi-transparent solar panels in the HiTechGH building (Yano et al., 2014). The 2021 WA Energy Strategy aims to decarbonize the energy sector with stepwise reductions: 70% below 1990 levels by 2030 and net zero emissions by 2050 (Jacobson et al., 2015; Washington State Department of Commerce, 2020). These potential changes in energy sources will result in reduction of the water and GHG footprints associated with energy production. In terms of design, many innovative technologies are promising: the use of solar collectors for heating and cooling can reduce the conventional HiTechGH energy use by about 44% (Ntinas et al., 2020). Underground air tunnel systems for heating and cooling the HiTechGH during winter and summer have also been explored (Ozgener and Ozgener, 2010).

4.6. Consideration for further research

One source of uncertainty in this study is that the cost assumptions of producing tomatoes in Alberta, CA were used in WA. However, the main costs of labor wages, electricity, and natural gas was adjusted to WA historical prices (see supplementary material SM3). There is a wide variety of GH technologies, and therefore we selected the most frequently used system in Canada, which appears reasonable as a precedent for cooler areas in the US. Future studies exploring HiTechGH technology innovations in Mexico and California, which includes a cooling system, could be more appropriate for warmer US regions where heating and lighting control are less important. This will also prevent loss of water from the system due to ventilation, with potential substantial reductions to the water footprint. This will however come with a higher energy footprint with additional energy related to cooling, and higher GHG and water footprints related to this increased energy needs as well. This further highlights the need to focus on clean energy sources. A more comprehensive cradle to grave life cycle analysis assessment will give a more complete picture of the footprints. Furthermore, in addition to the footprints and economics analyzed in this paper, there are other important aspects from the perspective of actual adoption of HiTechGH systems (e.g., size of investments, complex operations, and potential institutional barriers to adoption) that need consideration.

5. Conclusions

We simulated the production of fresh tomatoes in indoor high-tech greenhouse (HiTechGH) and open-field (OF) conditions. Our findings show that both systems are potentially economically feasible in our study region. We found that, on average, HiTechGH provides higher yields per area (6.4 times OF), with significantly higher energy (231 times OF), higher greenhouse gas (18 times OF) and slightly lower (0.74 times OF) water footprints. Therefore, scaling up tomato production can be accomplished either via a larger OF area with higher water footprints or with a smaller HiTechGH area with much higher energy and greenhouse gas footprints. HiTechGH comes with potential environmental benefits of reduced soil erosion and leaching of chemicals into surface and ground water. In order to support sustainable intensification of food production, HiTechGH system must prioritize reduction of environmental footprints. Reducing energy footprint with a focus on clean energy will have the double benefit of reducing not only the energy intensity but also greenhouse gas and water footprints and improve the overall sustainability of HiTechGH food production.

Author contributions

CS and FM conceived and designed the research. FM performed the data gathering, model setup, simulations, and analysis. KR, CS, and FM contributed to the interpretation and visualization of the results. KR, CS, and FM wrote the manuscript.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2022.130459.

References

Adam, C., Adcock, F.J., 2005. International Agricultural Trade Disputes: Case Studies in North America. University of Calgary Press.
AgWeatherNet, 2014. The Washington Agriculture Weather Network. Washington State University Prosser, WA.
Altes-Buch, Q., Quoilin, S., Lemort, V., 2019. Greenhouses: a Modelica library for the simulation of greenhouse climate and energy systems. In: Proceedings of the 13th International Modelica Conference, Regensburg, Germany, March 4–6, 2019, 157, pp. 533–542. https://doi.org/10.3384/ecp19157533.
Aroca-Delgado, R., Pérez-Alonso, J., Callejón-Ferre, Á.J., Velázquez-Martí, B., 2018. Compatibility between crops and solar panels: an overview from shading systems. Sustainability 10 (3).
Bailey, B., Hayman, G., 2002. Tomatoes: Guidelines for CO2 Enrichment: a Grower Guide, vol. 35. Horticultural Development Council.
Baskins, S., Bond, J., Minor, T., 2019. Unpacking the Growth in Per Capita Availability of Fresh Market Tomatoes. USDA-ERS. VGS-19C-01(March), 1–15.
Bosona, T., Gebresenbet, G., 2018. Life cycle analysis of organic tomato production and supply in Sweden. J. Clean. Prod. 196, 635–643.
Boulard, T., Raeppel, C., R Brun, F Lecompte, Hayer, F., Carmassi, G., Gaillard, G., 2011. Environmental impact of greenhouse tomato production in France. Agron. Sustain. Dev. 31 (4), 757–777.
Buendia, C., Tanabe, E., Kranjc, K., Baasansuren, A., Fukuda, J., Ngarize, M., Osako, S., Pyrozhenko, A., Shermanau, Y., Federici, P., 2019. 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories, the Intergovernmental Panel on Climate Change (IPCC).
Calpas, J., 2003. Commercial Greenhouse Tomato Production in Alberta. Government of Alberta. Agriculture and Forestry.
Campbell, G.S., Norman, J.M., 1998. An Introduction to Environmental Biophysics, 2° Edition. Springer-Verlag.
Cook, R., Calvin, L., 2005. Greenhouse Tomatoes Change the Dynamics of the North American Fresh Tomato Industry. *Economic Research Service*. US Department of Agriculture, p. 81 (April).

Darghouth, N.R., Wiser, R.H., Barbose, G., Mills, A.D., 2016. Net metering and market feedback loops: exploring the impact of retail rate design on distributed PV deployment. Appl. Energy 162, 713–722. https://doi.org/10.1016/j.apenergy.2015.10.120.

Davis, K.F., Gephart, J.A., Emery, K.A., Leach, A.M., Galloway, J.N., D'Odorico, P., 2016. Meeting future food demand with current agricultural resources. Global Environ. Change 39, 125–132.

Dhaliwal, D., Subramanyam, K.R., Trezevant, R., 1999. Is comprehensive income superior to net income as a measure of firm performance? J. Account. Econ. 26, 43–67.

D'Odorico, P., Davis, K.F., Rosa, L., Carr, J.A., Chiarelli, D., Dell'Angelo, J., Gephart, J., Macdonald, G.K., Seekell, D.A., Suweis, S., Rulli, M.C., 2018. The global food-energy-water nexus. Rev. Geophys. 56, 76. https://doi.org/10.1029/2017RG000591.

Edwards, D.R., Jolliffe, P.A., Ehret, D.L., 2004. Carbon status of CO_2-enriched tomato plants under commercial greenhouse conditions. Acta Hortic. 633, 279–286. https://doi.org/10.17660/ActaHortic.2004.633.34.

Eggelston, H.S., Buendia, L., Miwa, K., Ngara, T., Tanabe, K., 2006. Guidelines for national greenhouse gas inventories. Respirology. https://doi.org/10.1111/j.1440-1843.2006.00937_1.x.

Ernest, E., Johnson, G., 2017. Tomatoes Fresh Market. University of Delaware Cooperative Extension Vegetable Crop. *Budget-2017*, 1–2.

Evangelou, E., Tsadilas, C., Tserlikakis, N., Tsitouras, A., Kyritsis, A., 2016. Water footprint of industrial tomato cultivations in the pinios river basin: soil properties interactions. Water (Switzerland) 8 (11), 1–13.

Foley, J.A., Ramankutty, N., Brauman, K.A., Cassidy, E.S., Gerber, J.S., Johnston, M., Mueller, N.D., O'Connell, C., Ray, D.K., West, P.C., Balzer, C., Bennett, E.M., Carpenter, S.R., Hill, J., Monfreda, C., Polasky, S., Rockström, J., Sheehan, J., Siebert, S., Tilman, D., Zaks, D.P.M., 2011. Solutions for a cultivated planet. Nature 478 (7369), 337–342.

Fritzson, P., Engelson, V., 1998. Modelica — A unified object-oriented language for system modeling and simulation. In: Jul, E. (Ed.), ECOOP'98 — Object-Oriented Programming. Springer Berlin Heidelberg.

Ghoulem, M., K El Moueddeb, E Nehdi, Boukhanouf, R., Kaiser Calautit, J., 2019. Greenhouse design and cooling technologies for sustainable food cultivation in hot climates: review of current practice and future status. Biosyst. Eng. 183, 121–150.

Hartz, T., Miyao, G., Mickler, J., Lestrange, M., Stoddard, S., Nuñez, J., Aegerter, B., 2008. Processing Tomato Production in California. Process. Tomato Prod. Calif. https://doi.org/10.3733/ucanr.7228.

Hochmuth, G.J., Hochmuth, R.C., 2012. Production of Greenhouse Tomatoes - Florida Greenhouse Vegetable Production Handbook, vol. 3, pp. 1–18. IFAS Extension, University of Florida, 3.

Howitt, R., Medellín-Azuara, J., Macewan, D., 2014. Economic Analysis of the 2014 Drought for California Agriculture. Center for Watershed Sciences. University of California, Davis, California, p. 20p.

Irabien, A., Darton, R.C., 2016. Energy–water–food nexus in the Spanish greenhouse tomato production. Clean Technol. Environ. Policy 18, 1307–1316. https://doi.org/10.1007/s10098-015-1076-9.

Jacobson, M.Z., Ma, Delucchi, Bazouin, G., Dvorak, M.J., Arghandeh, R., Bauer, Z.A.F., Cotte, A., GMTH de Moor, Goldner, E.G., Heier, C., Holmes, R.T., Hughes, S.A., Jin, L., Kapadia, M., Menon, C., Mullendore, S.A., Paris, E.M., Provost, G.A., Romano, A.R., Srivastava, C., Vencill, T.A., Whitney, N.S., Yeskoo, T.W., 2015. A 100% wind, water, sunlight (WWS) all-sector energy plan for Washington State. Renew. Energy 86, 75–88, 2016.

Karakaya, A., Özilgen, M., 2011. Energy utilization and carbon dioxide emission in the fresh, paste, whole-peeled, diced, and juiced tomato production processes. Energy 36, 5101–5110. https://doi.org/10.1016/j.energy.2011.06.007.

Kerr, A., Dialesandro, J., Steenwerth, K., Lopez-Brody, N., Elias, E., 2018. Vulnerability of California specialty crops to projected mid-century temperature changes. Climatic Change 148 (3), 419–436.

Kim, E.J., Siegelman, R.L., Jiang, H.Z.H., Forse, A.C., Lee, J.H., Martell, J.D., Milner, P.J., Falkowski, J.M., Neaton, J.B., Reimer, J.A., Weston, S.C., Long, J.R., 2020. Cooperative carbon capture and steam regeneration with tetraamine-appended metal-organic frameworks. Science 369 (6502), 392–396.

Klein, R., Mcclure, G., Wilson, R., Giesler, L., Groskopf, J., Jackson-Ziems, T., Jansen, J., Jasa, P., Proctor, C., Tigner, R., Wegulo, S., Wright, R., 2018. 2019 Nebraska crop budgets.

Koytsoumpa, E.I., Bergins, C., Kakaras, E., 2018. The CO2 economy: review of CO2 capture and reuse technologies. J. Supercrit. Fluids 132, 3–16. January 2017.

Kozai, T., Niu, G., Takagaki, M., Plant factory, 2016. An Indoor Vertical Farming System for Efficient Quality Food Production. Elsevier, p. 405.

Laate, E.A., 2018. Economics of Production and Marketing Greenhouse Crops in Alberta. *Alberta Agriculture And Forestry*. Government of Alberta (October), 1–50.

Ljungqvist, H.M., L Mattsson, M Risberg, Vesterlund, M., 2021. Data center heated greenhouses, a matter for enhanced food self-sufficiency in sub-arctic regions. Energy 215, 119169.

LNI, 2020. History of Washington State's Minimum Wage [WWW Document]. Washingt. State Dep. Labor Ind. URL. https://lni.wa.gov/workers-rights/wages/minimum-wage/history-of-washington-states-minimum-wage.

Magan, J.J., Lopez, J.C., Granados, R., Perez-Parra, J., Soriano, T., Romero-Gamez, M., Castilla, N., 2011. Global radiation differences under a glasshouse and a plastic greenhouse in Almeria (Spain): preliminary report. Acta Hortic. 907, 125–130.

Marchi, B., Zanoni, S., Pasetti, M., 2018. Industrial symbiosis for greener horticulture practices: the CO2 enrichment from energy intensive industrial processes. Procedia CIRP 69 (May), 562–567.

Markoff, M.S., Cullen, A.C., 2008. Impact of climate change on Pacific Northwest hydropower. Climatic Change 87 (3–4), 451–469.

Mohamed Kheir, H.K., 2010. Validity of ASABE Standards in Estimating Total Operating Cost. University of Khartoum.

Moss, C.B., Koo, W.W., Schmitz, A., 2003. International agricultural trade disputes: case studies in North America. Int. Agric. Trade Policy Cent. PBTC 1–11, 03–15.

NASS, 2011. Agricultural chemical use: vegetable crops 2010 fertilizers. Natl. Agric. Stat. Serv. July 1–4.

Ntinas, G.K., Neumair, M., Tsadilas, C.D., Meyer, J., 2017. Carbon footprint and cumulative energy demand of greenhouse and open-field tomato cultivation systems under Southern and Central European climatic conditions. J. Clean. Prod. 142, 3617–3626.

Ntinas, G.K., Dannehl, D., Schuch, I., Rocksch, T., Schmidt, U., 2020. Sustainable greenhouse production with minimised carbon footprint by energy export. Biosyst. Eng. 189, 164–178.

OCR, 2016. Columbia River basin long-term water supply and demand forecast: 2016 Legisletive Report. In: Office of Columbia River. Washington State Legislative Report. State of Washington. Department of Ecology, p. 189, 16-12–001.

Ozgener, L., Ozgener, O., 2010. Energetic performance test of an underground air tunnel system for greenhouse heating. Energy 35 (10), 4079–4085.

Page, G., Ridoutt, B., Bellotti, B., 2012. Carbon and water footprint tradeoffs in fresh tomato production. J. Clean. Prod. 32, 219–226.

Pathak, T., Kearns, F., Maskey, M., Dahlberg, J., Bali, K., Zaccaria, D., 2018. Climate change trends and impacts on California agriculture: a detailed review. Agronomy 8 (3), 25.

Payen, S., Basset-Mens, C., Perret, S., 2015. LCA of local and imported tomato: an energy and water trade-off. J. Clean. Prod. 87 (1), 139–148.

Pérez Neira, D., Soler Montiel, M., Delgado Cabeza, M., Reigada, A., 2018. Energy use and carbon footprint of the tomato production in heated multi-tunnel greenhouses in Almeria within an exporting agri-food system context. Sci. Total Environ. 628–629, 1627–1636.

Poudel, M., Dunn, B., 2017. Greenhouse carbon dioxide supplementation. Oklahoma Cooperative Extension Service HLA6723 (March), 1–6.

Pretty, J., Bharucha, Z.P., 2018. Sustainable intensification of agriculture. In: Sustainable Intensification of Agriculture: Greening the World's Food Economy. Routledge.

PSL (Pound Sterling Live), 2020. He Canadian Dollar to U.S. Dollar Historical Exchange Rates Conversion Page for 2018. Available at. https://www.poundsterlinglive.com/best-exchange-rates/best-canadian-dollar-to-us-dollar-history-2018.

Rajagopalan, K., Chinnayakanahalli, K.J., Co Stockle, Nelson, R.L., Kruger, C.E., Brady, M.P., Malek, K., Dinesh, S.T., Barber, M.E.E., Hamlet, A.F., Yorgey, G.G., Adam, J.C., 2018. Impacts of Near-Term Climate Change on Irrigation Demands and Crop Yields in the Columbia River Basin, vol. 54.

Stöckle, C.O., Martin, S., Campbell, G., 1994. CropSyst, a cropping systems model: water/nitrogen budgets and crop yield. Agric. Syst. 46, 335–359.

Stöckle, C., Donatelli, M., Nelson, R., 2003. CropSyst, a cropping systems simulation model. Eur. J. Agron. 18 (3–4), 289–307.

Stöckle, C.O., Kemanian, A., Nelson, R., Adam, J.C., Sommer, R., Carlson, B., 2014. CropSyst model evolution: from field to regional to global scales and from research to decision support systems. Environ. Model. Software 62, 361–369.

Tasgal, P., 2019. The economics of local vertical and greenhouse farming are getting competitive - AgFunderNews. Ag Founder News 1–11.

Tilman, D., Clark, M., 2014. Global diets link environmental sustainability and human health. Nature 515 (7528), 518–522.

Tilman, D., Balzer, C., Hill, J., Befort, B.L., 2011. Global food demand and the sustainable intensification of agriculture. Proc. Natl. Acad. Sci. Unit. States Am. 108 (50), 20260–20264.

Torrellas, M., Antón, A., Ruijs, M., García Victoria, N., Stanghellini, C., Montero, J.I., 2012. Environmental and economic assessment of protected crops in four European scenarios. J. Clean. Prod. 28, 45–55.

UGA extension, 2017. Commercial Tomato Production Handbook | UGA Cooperative Extension, vol. 1312. University of Georgia, pp. 1–48.

U.S. Department of Energy (DOE), 2016. State of Washington: Energy Sector Risk Profile. https://doi.org/10.1177/002205740706600317.

U.S. Energy Information Administration, 2020. State Energy Price and Expenditure Estimates 1970 through 2018.

USDA, 2014. 2012 census of agriculture: farm and ranch irrigation survey. Nat. Agri. Stat. Serv. 3 (November), 266. https://doi.org/10.5860/choice.51-0845, 28.

USDA-ERS, 2019. Vegetables and pulses yearbook data. USDA Econ. Res. Serv. 89011, 1–28. https://doi.org/10.5860/choice.51-0845.

USDA-NRCS, 2006. US General Soil Map. Natural Resources Conservation Service. Available at. https://catalog.data.gov/dataset/u-s-general- soil-map-statsgo2-for-the-unUSDA Econ. Res. Serv.ited-states-of-america.

Vadiee, A., Martin, V., 2014. Energy management strategies for commercial greenhouses. Appl. Energy 114, 880–888. https://doi.org/10.1016/j.apenergy.2013.08.089.

van Kooten, O., Heuvelink, E., Stanghellini, C., 2008. New developments in greenhouse technology can mitigate the water shortage problem of the 21st century. Acta Hortic. 767, 45–52. https://doi.org/10.17660/ActaHortic.2008.767.2.

Vanthoor, B., P de Visser, C Stanghellini, van Henten, E.J., 2011a. A methodology for model-based greenhouse design: Part 2, description and validation of a tomato yield model. Biosyst. Eng. 110 (4), 378–395.

Vanthoor, B., Stanghellini, C., Van Henten, E.J., De Visser, P.H.B., 2011b. A methodology for model-based greenhouse design: Part 1, a greenhouse climate model for a broad range of designs and climates. Biosyst. Eng. 110 (4), 363–377.

Vazirzadeh, A., Jafarifard, K., Ajdari, A., Chisti, Y., 2022. Removal of Nitrate and Phosphate from Simulated Agricultural Runoff Water by Chlorella Vulgaris, vol. 802. Science of the Total Environment, p. 149988.

Washington State Department of Commerce, 2020. Washington 2021 State Energy Strategy: Transitioning to an Equitable Clean Energy Future.
Yano, A., Onoe, M., Nakata, J., 2014. Prototype semi-transparent photovoltaic modules for greenhouse roof applications. Biosyst. Eng. 122, 62–73.
Yorgey, G.G., Hall, S.A., Allen, E.R., Whitefield, E.M., Embertson, N.M., Jones, V.P., Saari, B.R., Rajagopalan, K., Roesch-McNally, G.E., Van Horne, B., Abatzoglou, J.T., Collins, H.P., Houston, L.L., Ewing, T.W., Kruger, C.E., 2017. Northwest U.S. Agriculture in a changing climate: collaboratively defined research and extension priorities. Front. Environ. Sci. 5 (August), 1–20.
Zarei, M.J., Kazemi, N., Marzban, A., 2019. Life cycle environmental impacts of cucumber and tomato production in open-field and greenhouse. J. Saudi Soc. Agric. Sci. 18, 249–255. https://doi.org/10.1016/j.jssas.2017.07.001.
Zeileis, A., Grothendieck, G., 2014. Zoo: S3 infrastructure for regular and irregular time series. J. Stat. Software 14 (6), 1–27.