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Life-cycle greenhouse gas assessment of Community Supported Agriculture in California's Central Valley

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Abstract

Many consumers are trying to reduce their food's environmental impact by purchasing more locally sourced food. One choice for local food is Community Supported Agriculture (CSA), in which farmers provide a share of produce on a regular basis to pre-paying farm members. The number of CSAs in the USA has grown from two in the mid-1980s to perhaps as many as 12,617 according to the latest US census of agriculture (2014). We use a case study approach to investigate the greenhouse gas (GHG) emissions associated with five CSA operations in the Sacramento Valley of California. By understanding the GHG emissions of CSAs and the practices that might be improved, we hope to support innovative strategies to reduce GHG emissions in these agricultural production systems. Input, production and distribution data were collected from each farm and reported in CO_2e emissions for 1 kg CSA produce at the pickup location. Results show large variation in total emissions, ranging from 1.72 to 6.69 kg CO_2e kg^{-1} of produce with an average of 3.94 kg CO_2e kg^{-1} produce. The largest source of emissions was electricity, contributing over 70% of total CO_2e emissions on average. Based on our findings, despite the seemingly similarities between these operations in terms of production site, acreage, customers and production practices, there is still a large amount of variability with regard to total GHG. Thus we argue coming up with a standardized production function for diversified production and deriving GHGs or calculating average total emissions overlooks the heterogeneity of the system. Food systems can never be reduced to a simple binary of *local is better* and *conventional is worse*, or its inverse *local is worse* and *conventional is better*, because of the complexities of the production and distribution systems and their relationship to GHG emissions. Yet, we can say that localized production systems that are low in electricity use (or use renewable energy sources) and use efficiently-produced compost use have lower GHG emissions than those that do not.

Key words: community supported agriculture, food miles, local food, carbon footprint, life-cycle greenhouse gas assessment, greenhouse gas

Introduction

> What is needed is a sophisticated public debate on food systems in which catch phrases, such as 'food miles,' which were useful to initially capture media attention, now give way to more nuanced approaches based on strategic case studies of specific retail systems and/or key commodity sectors.
>
> — Coley et al. (2009, p. 154)

An increasingly popular way consumers seek to reduce their household environmental impact is by buying their food from local farms. This change is meant to reduce greenhouse gas (GHG) emissions and many other negative social and environmental consequences from conventional (high industrial input) agriculture and the broader conventional food system. 'Local' as a descriptor has a number of connotations in the current US culture – small-scale, sustainable, equitable, etc., but as many increasingly realize, not all local foods are created equal (Cleveland et al., 2011). In fact, local foods may not be produced at small-scale, sustainably nor with equity. However, other concepts, especially Lyson's (2004) 'civic agriculture,' capture a localism that is more in line with common connotations of 'local,' especially as it is practiced by smallholders in the alternative food movement.

Civic agriculture refers to 'community-based agriculture and food production activities that not only meet consumer demands for fresh, safe, and locally produced foods but create jobs, encourage entrepreneurship, and strengthen community identity. Civic agriculture brings together production and consumption activities within communities' (Lyson, 2004, p. 2).

One important element of civic agriculture is Community Supported Agriculture (CSA). CSA operations commonly provide a share of produce on a regular basis – usually vegetables but often including fruit and eggs, and sometimes other products like flowers, grain, dairy and/or meat – to pre-paying farm. In the original conception of CSA, by paying upfront, members share with the farmer the rewards and risks of agricultural production (Henderson and Van En, 2007). CSA farmers typically have strong commitments to organic, agroecological production methods and biological diversity, cultivating on average 44 different crops in California (Galt et al., 2012). The number of CSAs has grown in the USA from two in the mid-1980s to an estimated 3637 in 2009 (Galt, 2011) to perhaps as many as 12,617 according to the latest US census of agriculture (2014), making it an increasingly important outlet for fresh produce sales.

The increase in CSAs may be driven by a number of factors related to public perception of the food system. One is consumers' desire to reduce 'food miles,' a concept that became popular in the early 2000s as a convenient shorthand for environmental damage and inefficiency in conventional food systems (Pirog et al., 2001). Yet, research has since shown that food miles are not an appropriate proxy for environmental damage from transportation in the conventional food system (Smith et al., 2005; Weber and Matthews, 2008; Coley et al., 2009; Duram and Oberholtzer, 2010). One reason that food miles do not communicate transportation-related environmental burdens well is that it focuses only on distance while ignoring the mode of transport. Transportation modes vary enormously in their efficiencies; e.g., moving goods by train is far more efficient per unit GHG emissions than moving the same amount of goods the same distance by truck (Dutilh and Kramer, 2000). Additionally, the focus on food miles can obscure the effect of regional climate and heterogeneity of yields, and the contribution of very important processes – production, processing, packaging and storage – in overall GHG emissions associated with a food item (Brodt et al., 2013).

Thus, environmental analysis of localized food systems needs to take into account environmental flows *throughout the entire supply chain*. Life-cycle assessment (LCA) and life cycle GHG assessment (or carbon footprint) have been used to evaluate the environmental effects of conventional agricultural and food products from farm-to-fork or cradle-to-consumer, including production, transportation and storage (Jones, 2002; Carlsson-Kanyama et al., 2003; Eshel and Martin, 2006; Weber and Matthews, 2008; Meisterling et al., 2009; Roy et al., 2009; Liu et al., 2010; Schmidt, 2010; Cooper et al., 2011; Brodt et al., 2013; Costello et al., 2016). Most of these LCAs have focused on fresh produce from conventional agricultural and food systems (Table 1). These studies tend to show considerable range of potential life cycle GHG emissions within vegetables, with two orders of magnitude between the highest and lowest emitting systems. Some of this variability comes from different kinds of vegetables, which vary greatly in the ratio of inputs to yields. For example, 1 kg of carrots produced, distributed and consumed within Sweden emits 0.25 kg CO_2e kg^{-1} compared with 3.1 kg CO_2e kg^{-1} for tomatoes under similar conditions (Table 1). Differences in transportation, particularly mode, add a great deal more variability in GHG emissions for fresh vegetables; for example, 1 kg of green beans flown into the UK from Kenya emits 10.7 kg CO_2e (Milà i Canals et al., 2008) (Table 1).

Very little is known about GHG emissions from diversified vegetable production systems. Thus, life cycle-based assessment can provide important information about these systems (Edwards-Jones et al., 2008). CSA as a production system has a number of noteworthy elements that make it interesting, though difficult, to analyze with LCA. These notable features typically include (1) reliance on agroecological methods, particularly an ethic of closing nutrient cycles on the farm and sourcing nutrients locally and through organic matter like compost and green manures; (2) use of biological control, cultivation and other cultural practices like plastic row covers for weed and pest control rather than manufactured pesticides; (3) very high levels of cultivated agrobiodiversity, including a large number of crops in a small area; (4) highly variable yields; and (5) in our study's focus area of California, use of drip irrigation to maximize irrigation efficiency (Galt et al., 2011). Most of these production practices differ greatly from conventional vegetable production systems, which more readily lend themselves to LCA since (1) a single crop variety and relatively standardized inputs are spread over very large areas, and (2) information about production practices is widely available due to years of production and research by industry and academics (see UC Davis Cost and Return Studies).

This assessment seeks to answer the following questions: What is the carbon footprint of CSAs as regional production and distribution systems? How much variability exists among emissions from CSA production systems in a small geographic area? Where do opportunities exist along the CSA supply chain for increasing environmental benefits or reducing environmental harms in relation to GHGs? To answer these research questions, we collected data from five CSA vegetable farms in the Sacramento Valley of California. We chose a geographically explicit approach focused on a single region since production norms, seasonality and market proximity should impact

Table 1. 100-year Global Warming Potential (GWP_{100} kg CO_2e) for 1 kg of various produce items, as calculated by other authors.

		System				
Food	**Country**	**P**	**T**	**H**	**kg CO_2e kg^{-1}**	**Source**
Carrots	Denmark	√			0.12	Mogensen et al. (2009), p. 124
Potatoes	Denmark	√			0.16–0.22	Mogensen et al. (2009), p. 120, 124
Carrots: domestic, fresh	Sweden	√	√	√	0.22	Carlsson-Kanyama and González (2009)
Strawberries: organic	USA	√			0.23	Venkat (2012), p. 638
Potatoes	UK	√			0.24	Williams et al. (2006)
Carrots	Sweden	√	√		0.25	Carlsson-Kanyama (1998), p. 530
Strawberries: conventional	USA	√			0.34	Venkat (2012), p. 638
Broccoli: conventional	USA	√			0.35	Venkat (2012), p. 638
Onions	Denmark	√			0.38	Mogensen et al. (2009), p. 124
Broccoli: organic	USA	√			0.41	Venkat (2012), p. 638
Potatoes: cooked, domestic	Sweden	√	√	√	0.45	Carlsson-Kanyama and González (2009)
Strawberries	UK	√			0.7	Williams et al. (2009), p. 261
Blueberries: organic	USA	√			0.72	Venkat (2012), p. 638
Tomatoes	Spain	√			0.74	Williams et al. (2009), p. 260
Apples: fresh, by boat	Sweden	√	√	√	0.82	Carlsson-Kanyama and González (2009)
Blueberries: conventional	USA	√			0.83	Venkat (2012), p. 638
Oranges: fresh, by boat	Sweden	√	√	√	1.2	Carlsson-Kanyama and González (2009)
Green beans: South Europe, boiled	Sweden	√	√	√	1.3	Carlsson-Kanyama and González (2009)
Green beans: domestic, fresh	UK	√	√	√	1.42–1.55	Milà i Canals et al. (2008), p. 41
Green beans: domestic, frozen	UK	√	√	√	1.72	Milà i Canals et al. (2008), p. 41
Broccoli: domestic, fresh	UK	√	√	√	1.94	Milà i Canals et al. (2008), p. 23
Tomatoes	UK	√			2.2	Williams et al. (2009), p. 260
Broccoli: imported from Spain, fresh	UK	√	√	√	2.22	Milà i Canals et al. (2008), p. 23
Vegetables: frozen, by boat, boiled	Sweden	√	√	√	2.3	Carlsson-Kanyama and González (2009)
Broccoli: domestic, frozen	UK	√	√	√	2.64	Milà i Canals et al. (2008), p. 23
Tomatoes	Sweden	√	√		3.1	Carlsson-Kanyama (1998), p. 530
Tomatoes greenhouse)	Denmark	√			3.5	Mogensen et al. (2009), p. 120
Tomatoes	UK	√			9.4	Williams et al. (2006)
Green beans: imported from Kenya, fresh	UK	√	√	√	10.7	Milà i Canals et al. (2008), p. 41
Tropical fruits: fresh, by plane	Sweden	√	√	√	11	Carlsson-Kanyama and González (2009)

P, production and on-farm storage; T, transportation; H, household storage and cooking.

GHG emissions. Data were collected on all production inputs and processes, as well as marketed yields. This allowed us to calculate the cumulative global warming potential (GWP_{100} kg CO_2e) associated with our main functional unit: 1 kg of fresh diversified vegetables from a CSA share. By understanding the GHG emissions of CSAs and the practices where improvements might most easily be made, we hope to support innovative strategies to reduce GHG emissions in these systems.

Methods

Here we model GHG emissions of CSA from three main sources: the CSA production system at the farm level, the production and transportation of inputs used in the CSA production system and the emissions transporting produce to consumers. Figure 1 shows the system boundary of our analysis and the major processes and inputs included in our estimates. The farm production system includes growing, harvesting, storing and the farms distribution of the CSA shares but does not include the member transport of product to their home.

Data were collected through interviews with five farms in the Sacramento Valley with emissions calculated over one calendar year. All of the farming operations specialize in diversified vegetable production, supplemented with a small amount of fruit. None of the selected operations have farm animals. All of the interviewed farmers plant cover crops and incorporate plant residue into their fields. The farmers also apply additional amendments to improve soil fertility. Four of the five farms produce their own compost using horse manure and bedding from nearby horse boarding farms. Other farm characteristics for each CSA are shown in Table 2. The five farms have similar sales channels and strong adherence to agroecological farming principles and practices (Miles and Brown, 2005; Gliessman, 2007), something common to the broader population of CSAs in the region (Galt et al., 2012). While the number of CSA members per operation in California varies widely, the average per operation was 60 members, and as shown in

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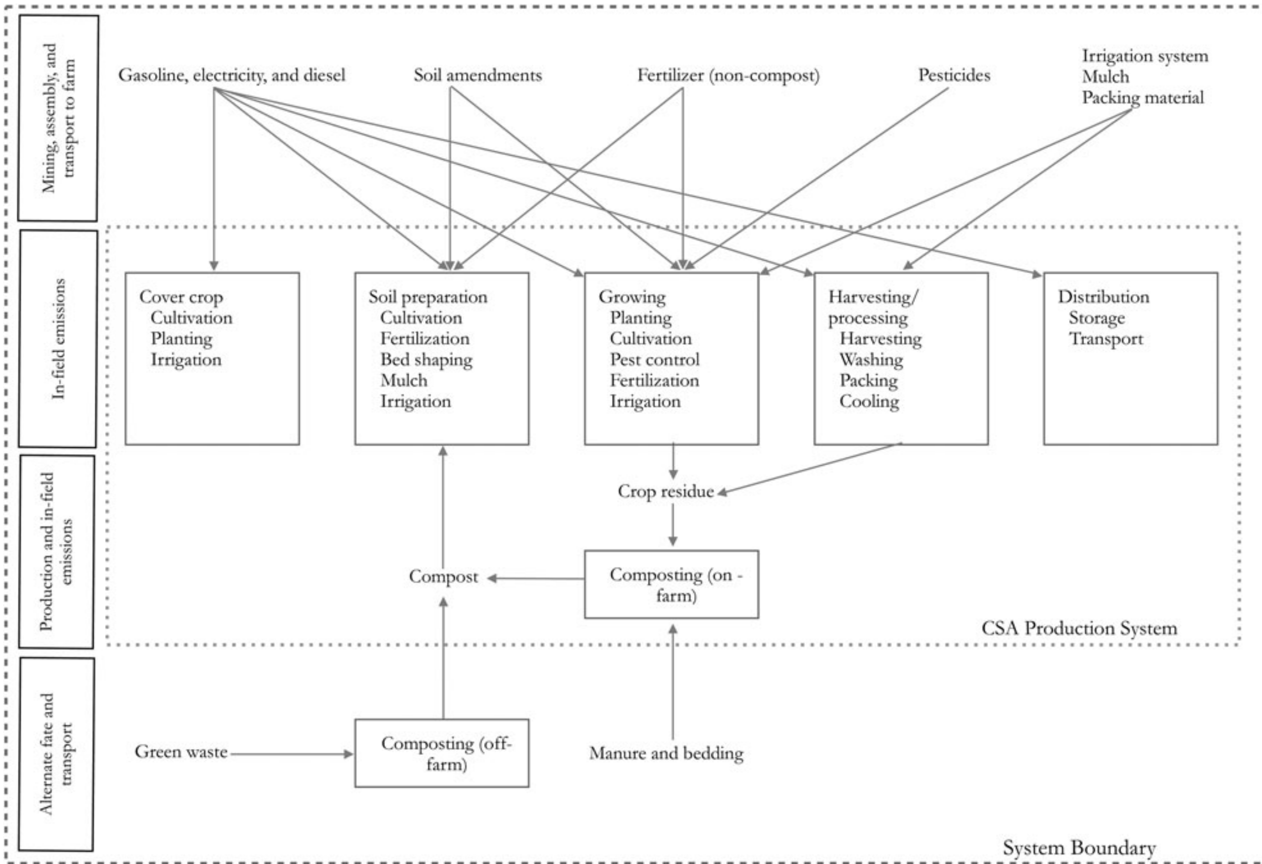

Figure 1. Analysis boundaries and CSA production process.

Table 2, the five selected CSAs have similar membership numbers (Galt et al., 2011). Additionally, median farm size for horticulture-focused CSAs in the region is 6.88 ha (ibid), again as shown in Table 2, the five selected CSAs are similar to that median size. Thus, the five farms are representative of vegetable-focused CSAs in California's Central Valley.

We quantified the inputs and direct emissions at the farm level using an attributional approach with the creation of a life cycle inventory (LCI) (Brander et al., 2008). Since CSA is a dispersed and intentionally non-standardized agricultural production and distribution system, applying LCI methodology requires some adaptations, detailed below.

The CSA production cycle is a non-standardized and complex process. CSA farms consist of patchworks of dozens of different annual and perennial crops with a wide range of maturity dates for even the same crop since the goal of most CSAs is to produce a wide range of vegetables over the entire growing season, which is year-round in this area of California (Galt et al., 2012). Each season and field may have different requirements in terms of irrigation, tillage, nutrient application and pest management. Although highly variable, the vegetable production process for California CSAs generally has five steps: (1) cover cropping, (2) field preparation, (3) growing, (4) harvesting/packaging and (5) storage/distribution. Each of these steps in the CSA life cycle requires different inputs. We included the GHG emissions associated with each to provide a full assessment of total emissions for the production and distribution system until it reaches the consumer.

All produce distribution is modeled as taking place within the Sacramento Valley. All of the included CSAs distribute only within their immediate region. Two of the farms have on-farm pick-up and the other three have centralized neighborhood drop-off/pick-up. To account for this difference in the model, we attempted to conduct a survey of CSA members regarding their personal transportation but were only able to secure responses from members of Farm 1, 3 and 4. We did not feel comfortable modeling member transport; therefore our system boundary ends at the CSA pickup site, either on farm or at a secondary location. As a result, the model may advantage the farms with on-farm pick-up and disadvantage the farms with centralized pick-up because farms with centralized pick-up were assigned the emissions attributed to transporting the product from their farm while the emissions attributed to picking up a box from a farm are outside the bounds of the study. Consumer transportation, handling, storage, consumption and disposal are not included in the assessment.

Final emission estimates for the entire system, including on- and off-farm sources, are reported in CO_2e

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Table 2. CSA characteristics.

	Farm 1	Farm 2	Farm 3	Farm 4	Farm 5
CSA characteristics					
Cropland (ha)	8.1	2.2	4.9	4.9	4.0
Cropland devoted to CSA (ha)	2.4	0.22	4.8	1.4	3.1
CSA marketed yield (kg ha^{-1})	805	801	949	534	919
Members in 2010	80	50	66	65	35
Start year of the farm	1992	2008	1976	2003	2003
Start year of CSA	2002	2008	1996	2005	2007
Organic	Certified	Not certified	Certified	Not certified	Not certified
Business status	Non-profit	For-profit	Non-profit	For-profit	For-profit
Density	Urban	Urban	Urban	Rural	Rural
Profitability	Profitable	Profitable	Profitable	Profitable	Break even
Distribution system	Centralized neighborhood drop-off/pick-up	Centralized neighborhood drop-off/pick-up	On-farm pick-up	Centralized neighborhood drop-off/pick-up	On-farm pick-up
Electricity					
Main electricity uses	25HP electric water pump, refrigerated storage unit	Electric water pump, photovoltaic solar panels	2 window AC units, swamp cooler, 100HP electric water pump	Electric water pump, refrigerated storage unit	New electric water pump, 500 sq ft refrigerated storage unit
Pumping use (KWh)	Not available	Not available	12,800	8460	Not available
Other use (KWh)	Not available	Not available	24,400	2460	not available
KWh ha^{-1}	3760	NA	7660	2250	2930
Machinery, fuel, and fertilizer use					
Farm machinery	45HP tractor, large van	75 HP 2006 tractor, compost spreader, ATV, mower	Six tractors (110 HP 1995, 80 HP 1982, 15HP 1982, 50HP 1969, 25HP 1953, 25HP n.d.) 25HP mower, 13HP 1965 harvester, Mule utility vehicle, weed whacker	Four tractors (1948, 1963, 1972, 1952), small truck, Mule utility vehicle, walk-behind tiller, weed whacker	34HP 2006 tractor, walk-behind tiller, small 2006 pickup truck (Tundra), weed whacker
Diesel (L ha^{-1})	88	228	653	97	344
Gasoline (L ha^{-1})	128	249	318	359	322
Soil amendments					
Greenhouse input/s	Coco peat, vermiculite, perlite	(No greenhouse)	Peat moss, perlite	Peat moss, perlite	Peat moss, vermiculite
Soil amendment/s	Lime	Gypsum	Gypsum	Gypsum	Lime, soft rock phosphate
Pesticide	Sulfur	None	Sulfur	Copper sulfate	None
Fertilizers	Kelp, fish emulsion, feather meal, on-farm compost, off-farm compost, cover crop	Fish emulsion, on-farm compost, off-farm compost, cover crop	Fish emulsion, feather meal, on-farm compost, cover crop	Feather meal, on-farm compost, off-farm compost, potash, cover crop	Fish emulsion, blood meal, potash, cover crop

emissions for 1 kg CSA produce. To summarize, the sources of GHGs considered in this study include: emissions from production and transportation of annual inputs (fertilizer and other soil amendments, pesticides, mulch, irrigation components, plant start flats and packaging); emissions from electricity and fuel (gasoline and diesel) consumption for farm machinery, storage and transport; and emissions from cover cropping and on-farm and off-farm composting. Emissions were only calculated for inputs that were used within the year. For example, we included drip tape that is replaced annually or every 2 years, but did not include aluminum pipes that last decades. The model does not account for emissions associated with manual labor, as a result shifting to less efficient manual labor in the production system may appear as a GHG-saving activity. With very few exceptions (Piringer and Steinberg, 2006; Nguyen and Gheewala, 2008) the environmental impacts associated with human labor have been systematically excluded from LCA studies. The most common reason for this is that labor-force maintenance-related environmental impacts (food consumption by workers; transportation to and from work; energy for shelter, etc.) would occur regardless of the studied system. Emissions from CO_2, CH_4 and N_2O, were converted to CO_2e using 100-year IPCC GWP values (Myhre et al., 2013). We did not include the manufacturing, wear and tear, and maintenance of equipment used in producing, storing and transporting the CSAs' produce, since the average lifespan of the equipment is longer than 20 years. The end-of-life of materials is also not included.

Data collection for CSA inputs and practices was conducted in 2011 using in-depth, standardized, on-site interviews with the five CSA farmers (interview protocol is available in Appendix A). The data collection focused on the 2010 production year. Additional follow-up communications were necessary to collect all of the data.

An inventory of almost all non-energy input use was determined for each farm operation. Excluded inputs were seeds, purchased transplants, relatively uncommon, unstandardized and small-dose soil amendments such as worm castings and compost tea. Seeds and purchased starts were excluded since farmers produced more than 40 different crops, purchased from a large range of providers, information on seed and transplants is unavailable and overall contribution to GHG emissions is likely low (Brodt et al., 2013). Inputs included fertilizers, soil amendments, pesticides, irrigation, mulch, plastic containers for plant starts and packaging material (a detailed list of inputs is presented in the Appendix B). Data were collected in different units based on how they were reported. While some inputs were reported in units of mass, other inputs were reported in volume, by count, or, for plastic, in linear feet. For non-compost soil amendments and pesticides reported in volume, we used material safety data sheets to estimate density and active ingredient quantity. For plastic inputs measured in surface area or linear feet, we used Alibaba (2011), an online wholesaler, to estimate mass. A list of all inputs was compiled and associated GHG emissions were obtained from the Ecoinvent Centre database (2008), other published databases and models, and government reports (Murtishaw et al., 2005; Novoa and Tejeda, 2006; California Air Resources Board, 2007). For nearly all inputs, life cycle inventories characterizing their production were included; the exceptions were for inputs that are byproducts from other industries, specifically fish emulsion, feather meal and kelp. For all inputs, including those considered byproducts, emissions for transportation to the farm were included.

Data for characterizing energy use on the farm, including fossil fuels and electricity, was collected in a similar way. For fossil fuel use, the farmers were asked to report total fossil fuel use for their farm; farmers reported in gallons and/or tractor hours. Tractor hours were converted to total gallons and emissions using a bottom-up model, constructed by Kendall et al. (2015), using parameters obtained from the California Air Resource Board Off-Road Database (2007). The farmers were also asked about their fuel use for off-farm vehicles and asked the proportion of driving attributed to input pick-up and CSA share distribution. Two of the CSAs had only an on-farm location for their members to collect their CSA shares. The CSA farmers were also asked to report all electricity use on the farm. All farms relied upon electric water pumps for irrigation. Some of the CSAs had on-site refrigerated storage for their fresh produce, while other farms were able to harvest and deliver the same day without needing additional storage. Emissions from electricity use were calculated using the US Western Grid Energy Mix (PE International, 2012).

While a variety of emissions may occur from agricultural fields and soils, only N_2O emissions from soil amendments and cover crops were estimated and included. We did not attribute CO_2 emissions from compost to the production system, following standard procedure for biologically-derived carbon (De Klein et al., 2006). We also did not model carbon sequestration or carbon losses from the soil given that soil carbon sequestration is a complex process dependent on soil type, previous land use, climate, irrigation and cultural practices. Extensive data collection over a period of years or biogeochemical modeling would be required to reasonably estimate soil carbon changes for the CSAs in this study, which are outside the scope of this analysis. Yet, modeling these might lower emission calculations from the system (Kong et al., 2005; Leifeld and Fuhrer, 2010). For modeling N_2O emissions, we used Tier 2 IPCC methods (De Klein et al., 2006), assuming an emission factor of 0.01 for organic amendments and crop residues. Data were collected from farmers regarding cover crops and composting. Farmers reported cover crop in terms of species and acreage. Total biomass and nitrogen (N) content was calculated for each cover crop type using UC Davis' cover crop database

(University of California SAREP, 2006). Field emissions for on- and off-farm compost were modeled the same way, assuming that compost is approximately 50% water, with a carbon to N ratio of 30:1.

Non-field emissions from the production of compost were handled in the following way. Three farms used a combination of off-farm compost (purchased from industrial-scale facilities) and on-farm compost, one farm used only on-farm compost and the other farm did not use compost. Transportation emissions were modeled from the compost production site to the farm for the off-farm compost and for the raw manure/bedding for the on-farm compost. Off-farm compost was composed of landscaping green waste and food scraps. On-farm compost primarily composed of off-farm horse bedding and manure with a small amount of farm crop waste. On-farm compost production was modeled using home-compost pile emissions from Martínez-Blanco et al. (2010) and tractor emissions attributed to the production of on-farm compost were captured previously in the total tractor emissions. Using an economic allocation approach, total emissions for off-farm compost production were modeled using a study of industrial composting in Spain, with a similar Mediterranean climate to the Sacramento Valley (Martínez-Blanco et al., 2010) and allocated based on total revenue attributed to the sale of compost for the waste facility, which is approximately 25% (Carlton, 2011). Martínez-Blanco et al. (2010) found emissions attributed to the release of methane and nitrous oxide from home composting to be more than five times higher than those from industrial composting; with the economic allocation and transportation emissions, home composting was 20 times higher than off-farm composting in our model. It should be noted that fertilizer emissions are often based on kilogram of applied N. By standardizing emissions by kilogram of applied N, we can compare on- and off-farm compost to popular synthetic fertilizer. While on- and off-farm compost are around 1.3 and 1.5% N by weight (Sullivan and Costello, 2010), respectively, ammonia is 82% N, urea is 46% and ammonium nitrate is 34% (C.F. Industries, 2013). Yet, if we compare the GWP of these five fertilizers, on-farm compost is 24.05 kg $CO_2e\ kg^{-1}$ of N, off-farm compost is 0.96 kg $CO_2e\ kg^{-1}$ of N, ammonia is 2.6 $CO_2e\ kg^{-1}$ of N, urea is 3.2 $CO_2e\ kg^{-1}$ of N and ammonium nitrate is 9.7 $CO_2e\ kg^{-1}$ of N (Snyder et al., 2009). Despite the differences in efficiency of N delivery by weight, off-farm compost has fewer emissions per kilogram of applied N. Also important to recognize are the additional services provided by compost. Martínez-Blanco et al. (2013) identified nine benefits: (1) nutrient supply; (2) carbon sequestration; (3) weed, pest and disease suppression; (4) crop yield; (5) soil erosion; (6) soil moisture content; (7) soil workability; (8) soil biological properties and biodiversity; and (9) crop nutritional quality. Compost emissions for on-farm composting in small-scale production systems should be some where between industiral and home production systems, further study is needed to better understand and more accurately model GHGs from small-scale, on-farm composting.

The functional unit of analysis is 1 kg of diversified produce. Thus, yields of each farm had to be determined. Determining yields in the CSA systems involved a variety of approaches. The ideal situation existed for Farm 4; the farmer kept detailed records on total farm production area by specific crop type and the annual amount sold for each crop. This allowed for accurately estimating weights of the year's total farm production for each vegetable type in the CSA. Other farms lacked this detailed data, thus requiring other methods. For Farm 3 and Farm 5, we mined the CSAs' 2010 newsletters, which include lists of all shares' products on a weekly basis for the year. Because many products are provided in bunches (rather than the number or specific weight), the mass of each bunch was estimated by weighing organic bunches of the product sold at a grocery store (Nugget Market) in Davis, California. We then multiplied the individual bunch weights by the frequency of product listed in the newsletters. For Farm 1, the farmer provided total hectares planted for each major crop type. Each area was then multiplied by average yields for each of these crop types (and their component vegetables) from diversified, small-scale farming systems (Jeavons, 2006) minus 23% of total yield due to losses from agricultural production and post-harvest handling and storage (Gustavsson et al., 2011). Farm 2 lacked all of these data (newsletter, bunch weight, yield and cultivated area), so yield data for it was estimated using the average kg ha^{-1} yield from the three farms for which direct data was available (Farms 3–5). More calculation details for estimating yield are provided in the Supplementary Materials. Because of the variability in yield between the different farms (Table 2), we also compared emissions per hectare and report GWP_{100} kg $CO_2e\ ha^{-1}$.

Results

Table 3 shows CO_2e emissions for 1 kg of CSA produce; data are shown averaged and disaggregated for each farm to illustrate variation (Miles and Brown, 2005). Emissions are broken down by major category of inputs: electricity, pesticides, plastics for production, plastics for packaging, on-farm soil amendments, off-farm soil amendments and vehicle and machinery (including on-farm, input pickup and produce distribution). On average, 1 kg CSA produce has a GWP_{100} of 3.94 kg CO_2e. This estimate does not incorporate any credits for the environmental services attributed to compost (Martínez-Blanco et al., 2013) including carbon sequestration that may occur in soils or credit for diverting waste by composting, nor direct land-use changes making it an estimate.

Table 3. 100-year Global Warming Potential (GWP_{100} kg CO_2e) for 1 kg of CSA produce in the Sacramento Valley Region.

Source	Farm 1	Farm 2	Farm 3	Farm 4	Farm 5	Mean	S.D.
Electricity	3.11	–	5.37	2.88	2.79	3.54	1.23
Pesticides	0.00	–	0.00	0.00	–	0.00	0.00
Plastics for production	0.01	0.03	0.20	0.01	0.05	0.06	0.08
Plastics for packaging	0.00	0.00	0.00	0.00	0.00	0.00	0.00
On-farm compost	0.12	1.06	0.72	0.00	–	0.40	0.48
Off-farm soil amendments	0.06	0.20	0.04	0.24	0.43	0.19	0.16
Vehicles and machinery (on-farm)	0.07	0.24	0.65	0.32	0.34	0.32	0.21
Vehicles (input pickup)	0.09	0.13	–	0.04	0.37	0.16	0.15
Vehicles (distribution)	0.13	0.06	–	0.22	–	0.14	0.08
Total	3.59	1.72	6.69	3.72	3.98	3.94	1.78

Figure 2 visualizes the GHG emissions for various input categories and shows that electricity has by far the greatest effect on overall emissions, accounting for 72% of emissions on average for the five farms. It is one order of magnitude greater than on-farm compost, off-farm soil amendments, on-farm vehicles and machinery; two orders of magnitude greater than plastics for production, vehicles for input pickup and vehicles for delivery; and three or more orders of magnitude greater than plastics for packaging and pesticides. The farms in the study used electricity to pump water, and to cool and store products. In other LCA studies of California agriculture, electricity has a similarly large impact due to irrigation. Venkat's (2012, p. 636) analysis of California almond production, one of the two crops for which electricity use is provided in detail, showed that electricity was the largest single category of GHG emissions, contributing 29.4% from production. Some LCA studies of vegetables often do not explicitly note their treatment of electricity on the farm (e.g., Mogensen et al., 2009), especially as it relates to cooling of newly harvested produce, while others do (e.g., Milà i Canals et al., 2008), making it difficult to directly compare results on the cooling process. Even when cooling is considered, electricity meters tend to provide information for an entire site of production, rather than specific processes, making attribution challenging (Milà i Canals et al., 2008).

The overall pattern that emerges when comparing the total emissions from CSA produce (Table 3) with emissions from other produce (Table 1) is that CSA produce is a little above the average. It is generally the same as tomato production (Table 1). There are instances of much higher GWPs for fresh produce, as with greenhouse tomato emissions of 9.4 kg CO_2e kg^{-1} (Williams et al., 2006) and instances of much lower (Williams et al., 2009). Typically, the produce presented with lower emissions does not include transportation to retail point as included in our system and it is not always clear whether electricity for cooling is considered at the farm level or beyond. It should also be noted that our estimate is on the high side because of conservative assumptions made, yet the consequences of these assumptions are likely small relative to electricity use.

The substantial variation between different CSAs is an important finding and one worth examining in terms of farm attributes (Table 3 and Fig. 2). Variability in emissions is to be expected given the variability in farming systems generally. For example, studies that examine inputs in great depth, such as pesticides, show substantial variation, often with orders-of-magnitude differences in farms located near one another (Burleigh et al., 1998; Galt, 2008). Often in carbon footprint studies this variation is not demonstrated because researchers only model one production system or will rely on a hypothetical production system defined by experts. Those few studies that compared multiple production systems in the same region have shown high levels of variation, up to 50% (Milà i Canals et al., 2007). The level of variation within CSA is considerably higher than that shown in other studies, ranging from a low of 1.72 kg CO_2e kg^{-1} CSA produce to a high of 6.69 kg CO_2e kg^{-1} CSA produce.

The large variation between CSA farms is attributed to three major sources, as revealed by the standard deviations for the various inputs (Table 3). Emissions from electricity consumption (S.D. = 1.23), on-farm soil compost (S.D. = 0.48) and on-farm vehicle use (S.D. = 0.21) are by far the most variable. While other inputs and practices (off-farm soil amendments, pesticides, plastics and off-farm vehicle use) are also quite variable, the magnitude of their contributions relative to electricity, on-farm soil amendments and on-farm vehicle use is so low that they contribute much less variation to overall emissions. CSA farms' use of compost and the origin of that compost is also a source of variability. Smaller scale, on-farm compost production is assumed to be less efficient (in terms of compost produced per GHGs emitted) than industrial scale commercial compost production (Martínez-Blanco et al., 2010).

Examining individual farms help to highlight further reasons behind the variability. Farm 2 was the most efficient CSA farm as measured by kg CO_2e kg^{-1} CSA produce. Farm 2 is part of a larger non-profit educational farming organization. The organization invested in renewable energy and has a solar photovoltaic-powered electric water pump. Farm 2 used a very large amount

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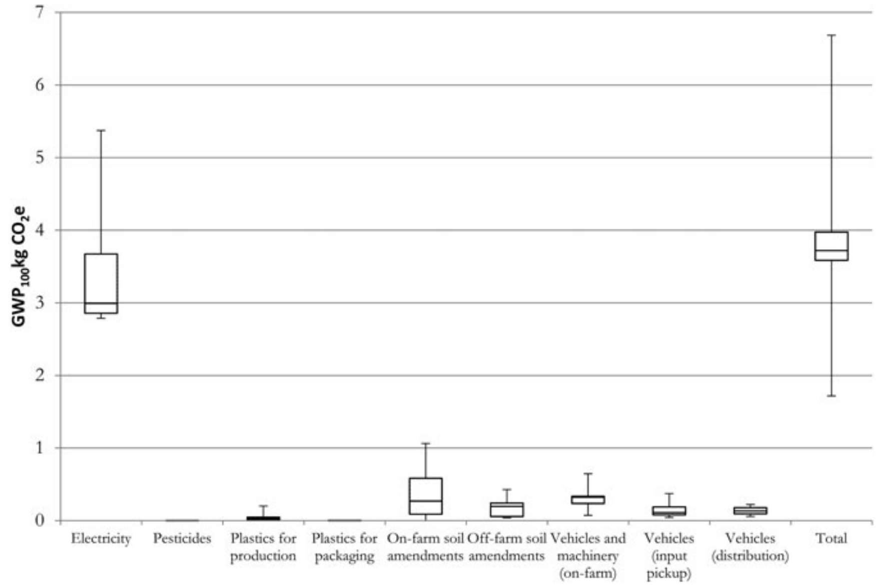

Figure 2. Average Global Warming Potential (GWP$_{100}$ kg CO_2e) for 1 kg of CSA produce by input category.

of on-farm compost per hectare, applying approximately 20,000 kg ha^{-1}. It was the smallest farm in our study both in terms of acreage and membership, and was able to rely primarily on hand labor, utilizing tractors only for bed preparation but their total emissions attributed to on-farm machinery were not largely different from Farms 4 and 5. The farm does not store produce and always delivers the same day as the harvest. This is generally only possible with a small membership size, since CSAs with larger member numbers tend to require much more complex harvesting and storage logistics. Farm 1 has the second lowest emissions, with 3.59 kg CO_2e kg^{-1} CSA produce. It used less than the average plastic, fuel, electricity and compost, relying primarily on off-farm compost. It also has centralized neighborhood drop-off/pick up sites and is the largest farm in the study. Farm 1 also received a grant to purchase a relatively new and efficient cooler, which helps to lower its overall electricity use compared with other farms with less efficient coolers. In contrast, Farm 3, the farm with the highest electricity use and consequently highest overall emissions, has temperature controlled greenhouse and window AC units and a swamp cooler to refrigerate stored produce. Farm 3 used on-farm compost, with an application rate above the average, with 11,780 kg ha^{-1}. Farm 5 did not apply any compost, using fish emulsion and blood meal for macronutrients.

Based on this small sample size it is difficult to identify statistically significant relationships between farm characteristics and GHG emissions, but it appears that as farms increase the number of hectares in CSA production they rely more on product life extension including cooling the product resulting in increased emissions. Further investigation is needed to support this observation and to potentially identify alternative strategies for larger-scale CSAs to minimize reliance on refrigerated cooling.

Table 4 shows the GHG emissions per hectare of land cultivated for CSA. The relative differences between Tables 3 and 4 are from yields. Farms with lower yields per hectare perform relatively better on an emissions-per-hectare basis, while farms with higher yields perform relatively worse; thus, Farm 4 appears relatively more efficient when looking at emissions per hectare while Farm 1 is relatively less efficient per hectare.

Discussion

Regularities and variability of GHG emissions within food systems

Carbon footprint assessments have uncovered some important regularities when it comes to food systems' impacts on the environment. Most prominently, they show meat-centered diets have much greater environmental impacts than plant-centered diets (Carlsson-Kanyama, 1998; Eshel and Martin, 2006; Weber and Matthews, 2008). The regularity of this finding reflects the causal mechanism behind it: great amounts of energy are lost to entropy as one moves higher in trophic level (Eshel and Martin, 2006). Studies have also shown that relative to the difference in meat- versus plant-based diets, the differences in transportation are not nearly as large, accounting for about 11% of emissions (Weber and Matthews, 2008). The exception is air freight, which has very high emissions relative to other forms of transportation (Dutilh and Kramer, 2000; Carlsson-Kanyama and González, 2009).

The public and some researchers seem to expect these kinds of regularities in the comparisons of environmental effects of local and organic food systems compared with conventional food systems. In other words, there is a tendency to want to say one type of system is always less

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Table 4. 100-year Global Warming Potential (GWP_{100} kg CO_2e) for 1 ha of CSA production in the Sacramento Valley Region.

Source	Farm 1	Farm 2	Farm 3	Farm 4	Farm 5	Mean	S.D.
Electricity	2500	–	5100	1540	2560	2930	1520
Pesticides	0.12	–	0.01	0.32	–	0.15	0.16
Plastics for production	6.42	23.4	192	4.13	43.476	53.8	78.6
Plastics for packaging	0.09	3.61	2.7	0.07	1.18	1.53	1.59
On-farm soil amendments	94.8	852	401	019	–	337	384
Off-farm soil amendments	46.2	158	37.2	129	394	153	145
Vehicles and machinery (on-farm)	58.2	76.9	613	173	309	246	288
Vehicles (input pickup)	73.0	103	–	23.4	343	136	172
Vehicles (distribution)	107	46.9	–	188	–	90.9	56.7
Total	2890	1260	6350	1990	3650	3230	1960

damaging than another. There are a number of reasons why such conclusions are not easily reached.

Our findings show that diversified vegetables produced by CSAs in California on average have moderate GHG emissions per kilogram produce compared with other vegetables. Yet, while above we compared the diversified CSA produce with individual vegetables in Table 1, it is somewhat misleading to do so for three main reasons. First, boxes of diversified CSA produce throughout the year in California often have a large amount of leafy green vegetables, which have much higher GHG emissions per kilogram since their yields per input used are lower than other types of vegetables and foods (Galt et al., 2013). Smil (2008) makes the same point when using energy efficiency as the metric of comparison. Second is the issue of seasonality. Yields have a very large impact on GHGs since GHGs are calculated per functional unit and there is a great deal of yield variability across operations and seasons. In California, it is often expected that CSAs produce year round, while conventional production typically coincides with periods for peak production. As a result, CSA produce at times of the year when the general efficiency of production is lower as compared with conventional production, which often leaves fields fallow during inefficient production times. Third, the regional context makes a large difference; production and distribution systems vary a great deal between regions, which means that vegetable production and distribution vary considerably between Sweden (where a great deal of food life cycle GHG studies have been done) and California. Thus, while it is tempting to compare directly, it is important to understand these differences in context that shape GHG emissions from CSAs and other local-and-organic food systems compared with the conventional food system.

Our findings also suggest that the variability within agroecologically-focused food systems may be considerably greater than in conventional food systems. This is likely due to CSA production systems being non-standardized. Even from the five cases in the same region presented here, we see the diversity of pathways that farmers use to solve production and distribution challenges. This results in variability of input categories due to different configurations (e.g., having consumers pick up on the farm versus a central drop off-site; inefficient cooling systems versus same-day delivery, etc.). If we sought to do these comparisons across large geographic space, a myriad of divergent pathways would arise. Diversified farming systems like CSA resist standardization because of their philosophical underpinnings, including working with nature's variability rather than subjecting it to homogenization and fitting production to local demand. Agroecological farming systems are also relatively new and not widely adopted. There is still a great deal of learning that needs to occur both on the part of the researcher as well as the practitioner. This variability means that the application of environmental assessment like LCA to CSA is a complex undertaking. Given the level of variability we have shown, more studies are needed if this variation is to be better explained.

More generally we argue that since there are many contingent mechanisms that structure food systems and because the dynamics of each are not nearly as regular as the energy and biomass transformations between trophic levels, we cannot expect consistent regularities across all local versus non-localized comparisons, nor can we expect that future and better research will somehow reveal these regularities. We expect that the outcomes of analyses that compare GHG emissions of local and non-localized food systems can never be accurately predicted for all systems, and therefore can never be reduced to a simple binary of *local is better* and *conventional is worse* (per the local trap, cf. Born and Purcell, 2006 and Galt, 2008), or its inverse *local is worse* and *conventional is better*, because of the complexities of the production and distribution systems and their relationship to GHG emissions. We can, however, conclude that localized production systems that are low in electricity use (or use renewable energy sources) and use efficiently-produced compost use have lower GHG emissions than those that do not. This insight allows for policy interventions in agriculture and routes for CSA farmers to pursue lowering their GHG emissions.

Room for improvement: targeting policy interventions

Before this study, there was a paucity of information for CSA farmers who want to reduce their GHG emissions. In the interviews, farmers were interested to know where they could make improvements for the largest change. Many farmers suspected that their tractor use or plastics use were the largest components of their emissions, which is understandable given the visibility of these inputs. Yet, in the overall analysis, the contribution of these inputs is relatively small compared with electricity use and soil amendments.

Our findings point to three important areas of intervention: (1) the need to promote on-farm renewable electricity generation, (2) the need to assist farmers with the purchase and use of energy efficient tools including tractors and refrigeration and (3) the vast importance of compost use in agricultural systems, particularly the use of off-farm produced compost. First, the GHG emissions of CSAs and other agroecologically-oriented farms with refrigerated storage facilities and electric water pumps can be greatly reduced through renewable energy generation. If the four CSAs with substantial electricity use were to create renewable energy systems, it would reduce emissions on average by 2.83 kg $CO_2e\ kg^{-1}$ of CSA produce, creating a net average of 1.11 kg $CO_2e\ kg^{-1}$ of CSA produce. Renewable energy is already produced on 22% of the CSA farms in the study region (Galt et al., 2011, p. 18), which shows a strong environmental commitment on the part of CSA farmers. If farmers were provided with stronger incentives to install renewable energy on their farms, it is likely that many CSA farmers would be among the first to adopt. Offsetting CSAs' on-farm electricity use with renewable electricity would result in CSAs being a very efficient way, in regards to GHG emissions, to produce and distribute fresh, healthy fruits and vegetables.

Lastly, it is important to note that our study only looks at the environmental impact associated with reducing GHG emissions and did not measure changes in biodiversity, nutrient efficiency and pollution, soil carbon and soil health, etc. Agroecologically-oriented agriculture has been shown to also improve all of these other environmental factors (Dale and Polasky, 2007; Sandhu et al., 2008, 2010). Moving conventional agriculture in the direction of incorporating particular production practices that more closely mirror those in agroecologically-oriented agriculture will require considerable policy interventions, however, since many pressures within the conventional food system exist to move farmers away from organically-based inputs (Buttel, 2006). Subsidizing compost use in agriculture broadly may well be one of the most economical ways of reducing GHG emissions (Favoino and Hogg, 2008). Additionally, providing carbon credits or other form of compensation for compost use can be an important way of promoting diversified farming systems, which have a host of other benefits (Iles and Marsh, 2012).

Supplementary material

The supplementary material for this article can be found at https://doi.org/10.1017/S1742170517000254.

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