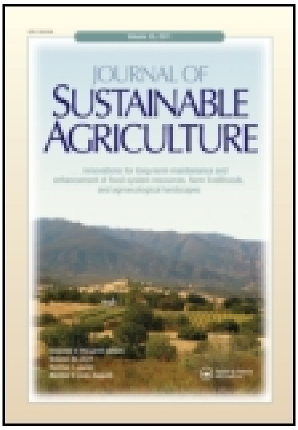

Journal of Sustainable Agriculture
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/wjsa20

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Accepted author version posted online: 28 Mar 2012. Version of record first published: 24 Jul 2012

To cite this article: Kumar Venkat (2012): Comparison of Twelve Organic and Conventional Farming Systems: A Life Cycle Greenhouse Gas Emissions Perspective, Journal of Sustainable Agriculture, 36:6, 620-649

To link to this article: http://dx.doi.org/10.1080/10440046.2012.672378

Journal of Sustainable Agriculture, 36:620–649, 2012

ISSN: 1044-0046 print/1540-7578 online
DOI: 10.1080/10440046.2012.672378

Comparison of Twelve Organic and Conventional Farming Systems: A Life Cycle Greenhouse Gas Emissions Perspective

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Given the growing importance of organic food production, there is a pressing need to understand the relative environmental impacts of organic and conventional farming methods. This study applies standards-based life cycle assessment to compare the cradle-to–farm gate greenhouse gas emissions of 12 crop products grown in California using both organic and conventional methods. In addition to analyzing steady-state scenarios in which the soil organic carbon stocks are at equilibrium, this study models a hypothetical scenario of converting each conventional farming system to a corresponding organic system and examines the impact of soil carbon sequestration during the transition. The results show that steady-state organic production has higher emissions per kilogram than conventional production in seven out of the 12 cases (10.6% higher overall, excluding one outlier). Transitional organic production performs better, generating lower emissions than conventional production in seven cases (17.7% lower overall) and 22.3% lower emissions than steady-state organic. The results demonstrate that converting additional cropland to organic production may offer significant GHG reduction opportunities over the next few decades by way of increasing the soil organic carbon stocks during the transition. Nonorganic systems could also improve their environmental performance by adopting management practices to increase soil organic carbon stocks.

K. Venkat wishes to thank the two anonymous referees for providing valuable comments that have helped improve this manuscript, and Emma Point for collecting and organizing the bulk of the raw agricultural data used in this study as part of her data research work for CleanMetrics Corp.

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KEYWORDS greenhouse gas emissions, life cycle assessment, organic farming, conventional farming, soil carbon sequestration

INTRODUCTION

The global market for organic food and drinks was estimated to approach $60 billion in 2010 (Organic Monitor 2010). Although the market share is still very small—about 3% of food sales in the United States (U.S. Department of Agriculture [USDA] 2009)—the organic segment has experienced rapid growth with global sales tripling in the 2000–2010 period. While agriculture as a whole contributes 13.5% of global greenhouse gas (GHG) emissions, it also has the potential to mitigate up to 6 Gt of carbon dioxide equivalents (CO_2e) per year mainly through soil carbon sequestration and climate change targets cannot be met without realizing a substantial part of this potential (Food and Agriculture Organization of the United Nations [FAO] 2009). Organic agriculture is generally considered to be more conserving of resources and soil quality (USDA 2011). The FAO (2009) has included organic and conservation agriculture among the innovative technologies required for climate change adaptation.

Given this background, there is a pressing need to understand the relative environmental impacts of organic and conventional farming methods and any benefits that may accrue from converting additional cropland to organic production. Any comparison of the environmental impacts of alternative production methods is best accomplished using life cycle assessment (LCA) techniques that can account for all major resource uses and emissions in the life cycle of a product (International Organization for Standardization 2006). Although there is now a growing literature on LCA-based comparisons of organic and conventional farming methods, only a subset of those studies compare GHG emissions on a per product unit basis.

Williams et al. (2006) analyzed the life cycle impacts of four crops (wheat, oilseed rape, potatoes and tomatoes) grown conventionally and organically in England and Wales. They found that organic wheat production used 27% less energy compared with nonorganic, but there was little difference in the case of potatoes. This reduction in energy due to avoided synthetic nitrogen manufacture was offset by lower organic yields and higher energy requirements for field work. Land use was also found to be 65–200% higher in organic systems due to lower yields and additional overheads such as cover crops. GHG emissions were 2–7% lower per unit product for organic field crops. For greenhouse grown tomatoes, organic production generated 30% more emissions per unit product than conventional production for the same mix of varieties, mainly due to the lower yields.

Meisterling et al. (2009) used streamlined hybrid LCA to compare organic and conventional wheat production and delivery in the United States using representative national data. Organic wheat flour generated about 16% lower GHG emissions than conventional flour; however, this difference vanished if the organic wheat was transported 420 km farther. Bos et al. (2007) examined model farms for the production of several organic and conventional crops in The Netherlands. GHG emissions per unit weight of product were higher on average for organic production, but lower for certain specific crops. Yields for organic crops were lower, which contributed to higher emissions per unit weight of product.

Pelletier et al. (2008) studied a hypothetical national transition from conventional to organic production of four major field crops (canola, corn, soy, and wheat) in Canada. They found that organic production would generate 23% lower emissions than conventional production, without considering soil carbon sequestration. This difference was almost entirely related to the production of synthetic nitrogen fertilizers for conventional farming. The organic models assumed that yields are 90–100% of conventional yields, that on-farm energy use is similar to conventional farms, and that all organic nitrogen inputs are derived from intercrops or cover crops.

De Backer et al. (2009) compared the production of leek in Belgium using both organic and conventional methods. Even though the conventional method produced higher yield, it still generated substantially higher GHG emissions per kilogram of product. Conventional leek used 22% less fuel on the farm per kilogram, but emissions from synthetic fertilizer production and the related on-farm nitrogen cycle were high enough to tilt the balance in favor of organics. In an LCA of Canadian wine production, Point et al. (2012) found through scenario modeling that there was virtually no difference between conventional and organic grape production, and high-yielding organic viticulture would only reduce GHG emissions marginally.

A recent LCA study of Swiss arable cropping and forage production systems (Nemecek et al. 2011) showed that organic farming was either superior or similar to the conventional integrated production, but with exceptions for some products such as organic potatoes which had higher environmental burdens. The main drawback of Swiss organic farming was identified as lower yield, which partly negated its other advantages.

Hokazono et al. (2009) used LCA to compare rice production systems in Japan and found that conventional farming generated about 6% lower GHG emissions than organic farming per kilogram of brown rice. This was attributed to the lower grain yields in organic farming.

Among studies that have looked at animal products, Thomassen et al. (2008) found no difference in the cradle-to-farm gate GHG emissions between milk produced in conventional and organic farms in The Netherlands. Cederberg and Mattson (2000) compared conventional and organic milk produced in Sweden and found that organic production generated about 10% lower emissions but used substantially more farmland. Williams et al. (2006) found that organic production generated higher GHG emissions for beef and poultry in England and Wales, but lower emissions for lamb and pork. Lindenthal et al. (2010) conducted a comparative LCA of dairy, poultry meat, eggs, bread, and vegetables in Austria, and found organic production to be consistently superior to conventional production on GHG emissions per kilogram of product.

Many of the LCA studies cited here found that organic methods produced lower yields and therefore required more land for a given production level. On energy use and GHG emissions, the results are decidedly mixed. While the lower yields push the energy use and emissions higher per product unit in organic production, the avoided production and use of synthetic inputs act as a countervailing force. The final outcome, then, often depends on the characteristics of the specific production systems being compared.

Each study in this literature review is specific to a particular geographical region (focusing largely on Europe), so it is not straight-forward to apply the results to other regions. In addition, the production data used in some of the studies did not correspond to specific production systems but were aggregated on a fairly broad scale. Two of the studies used model or hypothetical farms devised by the authors based on current practices in the broad regions studied (Bos et al. 2007; Pelletier et al. 2008), and two others used national aggregate production data for the commodities studied (Williams et al. 2006; Meisterling et al. 2009).

Changes in soil organic carbon (SOC) were not included in most of the studies. Meisterling et al. (2009) considered the general magnitude of the potential carbon sink in agricultural soils, but not as a function of local abiotic environmental conditions such as climate zone, moisture regime and soil type which all have a significant bearing on the actual magnitudes of soil carbon sequestration (Intergovernmental Panel on Climate Change [IPCC] 2006). Any detailed calculation of organic carbon sequestered in agricultural soils for specific farming systems requires knowledge of these abiotic conditions as well as management practices such as tillage and levels of carbon added to the soil. In many cases, this requires agricultural data to be collected at a smaller scale than national or broad regional data. In addition, MacRae et al. (2010) note that soil carbon sequestration usually reaches steady state after 15–33 years, which is an important factor to include in the calculation.

A number of meta-analyses comparing organic and conventional farming have been published in recent years based on prior LCA model studies and field trials (Gomiero et al. 2008; Mondelaers et al. 2009; Lynch et al. 2011). Many of the underlying studies did not use a standardized LCA approach with consistent system boundaries and assumptions; therefore, the conclusions must be used with some caution. The comparison metrics also varied between studies, with some using energy while others used GHG emissions or both. Some of the underlying studies (such as Hoeppner et al. 2006) do not specify whether energy use was calculated on a life-cycle basis including extraction and production of fuels as well as combustion.

Despite the methodological issues, the meta-analyses do provide some general insights that are similar to the individual LCA studies surveyed earlier. Mondelaers et al. (2009) found that organics generally exhibit lower land use efficiency (i.e., yield), which takes away any advantage they might otherwise offer. Gomiero et al. (2008) found lower energy consumption and GHG emissions in organic systems per land unit, but some crops showed higher energy consumption and emissions per product unit due to lower yields. Similarly, MacRae et al. (2010) note that organic systems generally demonstrate lower energy use and emissions per land unit; however, comparisons per unit of food output favor organics less strongly, largely due to yield differences between organic and conventional production systems.

Looking further at energy use, an analysis of 130 prior studies by Lynch et al. (2011) showed that organic fruit production (including specifically apples) generally required higher farm-level energy per product unit than conventional production; however, in the case of vegetables, they found that organics generally have the lower energy use. On the issue of soil carbon, Mondelaers et al. (2009) found higher levels of soil organic matter on organic farms but also noted that a number of studies did not find convincing evidence of differences mainly due to methodological limitations.

The motivation for the present study was to overcome some of the limitations in the existing LCA literature comparing the impacts of organic and conventional farming methods. In particular, the goals of this study were to: a) develop a robust, model-based life-cycle GHG emissions comparison of organic and conventional farming methods for a relatively large selection of crop products; b) use the best available production data for these crops from specific agricultural regions in the United States, including information on management practices; and c) account for the effects of soil carbon sequestration in relevant farming systems taking into account the climate zone, moisture regime and soil type for the geographical regions.

The present study compares the life cycle GHG emissions of 12 distinct crop products that are grown in the agricultural regions of California using both conventional and organic methods. Using publicly available agricultural production data for these crops, it applies standards-based LCA techniques to compare the life cycle GHG emissions per kilogram of each crop product grown using each production method. In addition, this study analyzes a hypothetical scenario of converting each conventional farming system to a corresponding organic system. Of particular interest in such a conversion is the potential for sequestering additional organic carbon in the soil.

FARMING SYSTEMS

The agricultural production data for the 12 organic and conventional crop products—consisting of information such as production region, yield, management practices, inputs, and other details—have been extracted from the detailed cost and return studies published by the University of California, Davis ([UCD] 2011). These cost and return studies are available for a wide variety of agricultural commodities produced in California, based on production practices considered typical for each crop and production region. They are considered sufficiently accurate for making production decisions, determining potential returns, preparing budgets, and evaluating production loans.

Table 1 lists the 12 crop products included in this study, each produced using both conventional and organic methods. The products were carefully

TABLE 1 Crop products, production methods, yield, production year, and data source

Crop product	Production method	Variety	Annual yield (kg/acre)	Production year	Primary agricultural data source
Blueberries	Conventional	Highbush	6350.36	2007	UCD (2007a)
Blueberries	Organic	Highbush	6350.36	2007	UCD (2007b)
Apples #1	Conventional	Fuji	4082.37	2007	UCD (2007c)
Apples #1	Organic	Golden Delicious, McIntosh, others	6350.36	1994	UCD (1994a)
Apples #2	Conventional	Granny Smith	18852.63	2001	UCD (2001)
Apples #2	Organic	Granny Smith, McIntosh, others	6803.96	1994	UCD (1994b)
Wine grapes #1	Conventional	Chardonnay	5443.16	2004	UCD (2004a)
Wine grapes #1	Organic	Chardonnay	5443.16	2004	UCD (2004b)
Wine grapes #2	Conventional	Cabernet Sauvignon	5216.37	2009	UCD (2009a)
Wine grapes #2	Organic	Cabernet Sauvignon	4535.97	2005	UCD (2005a)
Raisin grapes	Conventional	Thompson Seedless	1814.39	2006	UCD (2006a)
Raisin grapes	Organic	Thompson Seedless	1814.39	2008	UCD (2008)
Strawberries	Conventional		19494.69	2006	UCD (2006b)
Strawberries	Organic		13607.91	2006	UCD (2006c)
Alfalfa for hay	Conventional		5443.16	2007	UCD (2007d)
Alfalfa for hay	Organic		6350.36	2007	UCD (2007e)
Almonds	Conventional		907.19	2006	UCD (2006d)
Almonds	Organic		725.76	2007	UCD (2007f)
Walnuts	Conventional	Chandler	2267.99	2005	UCD (2005b)
Walnuts	Organic	Terminal bearing	453.60	2007	UCD (2007g)
Broccoli	Conventional		6636.12	2004	UCD (2004c)
Broccoli	Organic		6486.44	2004	UCD (2004d)
Lettuce	Conventional	Iceberg	14515.10	2009	UCD (2009b)
Lettuce	Organic	Leaf	8504.94	2009	UCD (2009c)

chosen so as to have comparable data for both conventional and organic production. The vast majority of the data are for recent production years. Every effort was made to ensure that the crop variety, production year and production region were the same or as close as possible for the farming systems being compared.

Table 2 lists the climate zone, moisture regime, land use category, tillage practice and soil carbon inputs for each farming system according to the classifications used by the Intergovernmental Panel on Climate Change in its most recent guidance for national GHG inventories (IPCC 2006). Note that the carbon inputs to soil are classified into four levels as defined below depending on the crop produced and the management practices:

- low carbon: all crop residues removed, or production of low-residue yielding crops such as vegetables;
- medium carbon: all crop residues returned to the field and prunings left on the ground, or supplemental organic matter added if residues are removed;
- high carbon: significantly greater organic carbon inputs compared to medium carbon due to practices such as production of high-residue yielding crops, prunings left on the ground, cover crops, use of green manures and use of compost, but without manure applied;
- high carbon–with manure: similar to high carbon, but with regular addition of animal manure.

METHODOLOGY

LCA Standards

Life cycle GHG emissions for the selected farming systems have been modeled and analyzed based on the PAS 2050:2008 standard (BSI Group 2008), which in turn builds on ISO standards (ISO 2006) by specifying additional requirements for the assessment of GHG emissions in the life cycle of products and services. The assessment period for all calculations is 100 years.

Within this framework, GHG emissions from agricultural soils and carbon sequestration are modeled based on the IPCC tier 1 guidelines (IPCC 2006). These include: direct and indirect nitrous oxide (N_2O) emissions due to the use of synthetic and organic nitrogen fertilizers and crop residues; carbon dioxide (CO_2) emissions due to the use of urea and lime; and CO_2 and N_2O emissions—or carbon sequestration in soils—due to changes in land use, tillage practice and carbon inputs to soil.

Functional Unit

The functional unit for the comparative LCAs of the farming systems is 1 kg of product. All GHG emissions are reported in kilograms of CO_2e,

TABLE 2 Production region, climate, moisture, land use, and management

Crop product, production method	Production region in California	Climate, moisture	Land use category	Tillage practice	Carbon inputs to soil
blueberries, conventional	Central/South Coast	Warm temperate, dry	Perennial or tree crop	No till	High carbon
blueberries, organic	Central/South Coast	Warm temperate, dry	Perennial or tree crop	No till	High carbon
Apples #1, conventional	Intermountain Region	Cool temperate, dry	Perennial or tree crop	No till	Medium carbon
Apples #1, organic	North Coast	Warm temperate, moist	Perennial or tree crop	Reduced till (cover crops/weeds disked)	High carbon
Apples #2, conventional	San Joaquin Valley North	Warm temperate, moist	Perennial or tree crop	No till	Medium carbon
Apples #2, organic	Central Coast	Warm temperate, moist	Perennial or tree crop	Reduced till (cover crops/weeds disked)	High carbon–with manure
Wine grapes #1, conventional	North Coast	Warm temperate, moist	Perennial or tree crop	No till	High carbon
Wine grapes #1, organic	North Coast	Warm temperate, moist	Perennial or tree crop	No till	High carbon–with manure
Wine grapes #2, conventional	North Coast	Warm temperate, moist	Perennial or tree crop	No till	High carbon
Wine grapes #2, organic	North Coast	Warm temperate, moist	Perennial or tree crop	No till	High carbon
Raisin grapes, conventional	San Joaquin Valley	Warm temperate, dry	Perennial or tree crop	No till	Medium carbon
Raisin grapes, organic	San Joaquin Valley South	Warm temperate, dry	Perennial or tree crop	No till	High carbon
Strawberries, conventional	South Coast	Warm temperate, dry	Long-term cultivated	Full till	Medium carbon
Strawberries, organic	Central Coast	Warm temperate, moist	Long-term cultivated	Full till	High carbon

(*Continued*)

TABLE 2 (Continued)

Crop product, production method	Production region in California	Climate, moisture	Land use category	Tillage practice	Carbon inputs to soil
Alfalfa for hay, conventional	Intermountain Region	Cool temperate, dry	Long-term cultivated	No till	Low carbon
Alfalfa for hay, organic	Intermountain Region	Cool temperate, dry	Long-term cultivated	Reduced till (tilled every 4 years)	Medium carbon
Almonds, conventional	San Joaquin Valley North	Warm temperate, moist	Perennial or tree crop	No Till	Medium carbon
Almonds, organic	San Joaquin Valley North	Warm temperate, moist	Perennial or tree crop	No till	High carbon
Walnuts, conventional	North Coast	Warm temperate, moist	Perennial or tree crop	Reduced till (row middles are disked)	Low carbon
Walnuts, organic	North Coast	Warm temperate, moist	Perennial or tree crop	No till	Medium carbon
Broccoli, conventional	Central Coast	Warm temperate, moist	Long-term cultivated	Full till	High carbon
Broccoli, organic	Central Coast	Warm temperate, moist	Long-term cultivated	Full till	High carbon–with manure
Lettuce, conventional	Central Coast	Warm temperate, moist	Long-term cultivated	Full till	Low carbon
Lettuce, organic	Central Coast	Warm temperate, moist	Long-term cultivated	Full till	High carbon–with manure

and comparisons of GHG emissions between different farming systems are on the basis of kilograms of CO_2e per kilogram of product. The perspective adopted here is basically that of product carbon footprinting.

System Boundary

The spatial boundary for the LCA of the farming systems is cradle to farm gate. This starts with extraction of raw resources from the ground and ends with the production of the crop products at the output gate of the farm. The system boundary includes the production and combustion of fuels such as gasoline, diesel and liquefied petroleum gas, as well as the generation and transmission of electricity. It also includes manufacture of all material inputs such as fertilizers and pesticides, as well as the transport of all such inputs to the farm. The PAS 2050:2008 standard (BSI Group 2008) specifically excludes from the system boundary all human energy inputs, animals providing transport services, and transport of farm employees to and from the farm.

Organic fertilizers and soil amendments such as compost and manure are derived from waste outputs generated by other systems. The raw materials for these inputs are assumed to enter the farming systems without any environmental burdens for manufacture. The modeling approach used here is consistent with the handling of recycled materials according to the "recycled content" method (Hammond and Jones 2010) where the system that produces the recyclable waste is responsible up to the point of delivering the unprocessed waste to a recycling facility, and then any subsequent processing and transport of that material are included within other systems that use the material in some form.

While manure is not further processed before application, compost is produced from organic waste using energy and water as additional inputs. Based on a recent review of commercial composting in California (California Air Resourced Board [CARB] 2011) and an LCA study of composting technologies in climatic conditions similar to California (Cadena et al. 2009), composting in confined windrows is used here as a representative method for calculating the environmental burden of composting. In this method, the weight of the finished compost is about 52% of the feedstock weight, and the process uses 65.5 kWh of grid electricity, 9 liters of diesel, and 0.02 cubic meters of water per tonne of feedstock (Cadena et al. 2009).

Since the agricultural data sources do not provide information on transport modes and distances for the material inputs, the modeling includes certain assumptions. Organic materials such as compost and manure are assumed to be sourced locally and transported by single-unit truck over a 112 km distance, obtained by averaging compost delivery distances in Northern and Southern California (CARB 2011; Kong et al. 2008). All other inputs—including synthetic fertilizers and pesticides—are assumed to be transported 1600 km by semi-trailer truck and 200 km by single-unit truck. All of these distance assumptions are tested using sensitivity analysis.

While most of the inputs used in the farming systems are modeled completely within the system boundary, there are two specific inputs that typically do not include sufficient information for complete process modeling. One is the production of purchased seeds, and the other is all of the custom work that is performed on a farm by hired contractors often using their own materials and equipment. The agricultural data sources generally only provide data on the economic value of these two inputs. In order to avoid cut-offs (Heijungs and Suh 2002), a hybrid approach is used in this study to convert these two economic values to GHG emissions based on an economic input-output LCA model (Carnegie Mellon University Green Design Institute 2010).

The temporal boundary covers the full production life span of each farming system. In the case of perennial or tree crops, the temporal boundary includes the entire useful life time of the crop, including the initial years required to establish the crop. In the case of annual crops, the temporal boundary includes all the years of continuous planting of that crop under the same management and production practices. In all cases, the cradle-to-farm gate GHG emissions are calculated over the full life span and then allocated uniformly to each year's production. The default production life span is assumed to be 30 years for all crops for the purposes of calculating annualized GHG emissions, and as shown in the results, this assumption is tested using sensitivity analysis.

Changes in Land Use or Management Practices

The baseline analysis of both conventional and organic farming systems in this study assumes that the SOC is at a spatially averaged equilibrium and is therefore neither increasing nor decreasing for the purposes of calculating net soil-derived GHG emissions. This steady-state assumption is generally considered to be valid when land use and management practices have been unchanged for a relatively long period of time such as the IPCC default of 20 years (IPCC 2006; Smith et al. 2008; Phetteplace et al. 2001; MacRae et al. 2010), and has been used in recent LCA studies of agricultural systems that do consider SOC (Pelletier et al. 2010).

When land use or management practices change, the organic carbon content of the soil transitions over a long period of time before settling into a new steady state. According to the IPCC tier 1 model (IPCC 2006), the SOC stock increases or decreases linearly over the transition period and then stabilizes at a new equilibrium value. In addition, the IPCC model also accounts for the additional N_2O emissions occurring as a result of the mineralization of organic nitrogen when soil organic matter decomposes.

However, it ignores other possibilities, such as an increase in N_2O emissions when switching from full-till to no-till depending on soil density and water content (Rochette et al. 2008; Gregorich et al. 2005; Six et al. 2004).

The IPCC soil carbon model is used in this study to evaluate an additional, hypothetical scenario: the transition from conventional to organic production for each of the 12 crop products. It is only during such a transition that additional carbon can be sequestered in the soil. Given the current interest in organic agriculture and the possibility that more farming systems might be converted to organic production in the coming years, it is important to understand the GHG mitigation potential of these transitional systems. Figure 1 illustrates the soil carbon profile in a typical transition from conventional production (using full till and a "Low Carbon" regime as defined earlier) to organic production (using reduced till and a "high carbon–with manure" regime), based on the SOC stock change factors for croplands as estimated by the IPCC based on published experimental data (IPCC 2006). These stock change factors represent the effect of a change in management practice at 20 years for the top 30 cm of the soil. The transition in this hypothetical example starts at year 40, which is the first year of production for the organic farming system, and ends at year 60. During the transition years, about 0.43 tonnes of carbon per hectare are added to the soil each year on average. The organic production ends at year 70, with the soil carbon at steady state for the final 10 years of production. Note that the assessment period is 100 years as specified by the IPCC.

The initial condition for the transition is assumed to be the conventional management method (i.e., tillage and carbon inputs) listed in Table 2 for each crop product. The transition then changes the inputs and the management method to that of the organic production for the same crop product. Any new soil carbon sequestered during the entire transition period is allocated uniformly to each year's production over the life span of the new system. The transition period—the number of years required for the soil

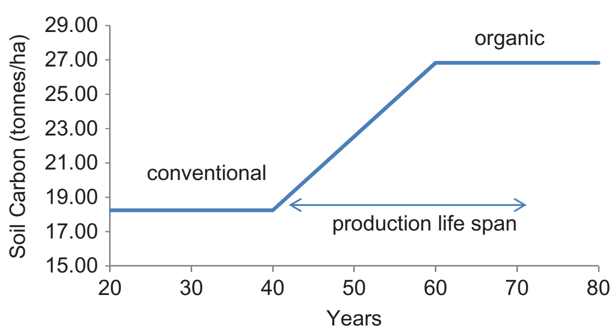

FIGURE 1 Soil carbon profile over a 20 year transition period in a typical conversion from conventional to organic production, based on IPCC (2006) (color figure available online).

carbon to reach steady state again—is assumed to be nominally 20 years (which is the IPCC default transition period), and then this assumption is tested using sensitivity analysis. The analysis further assumes that all soils are nominally low-activity clay (LAC), and this assumption is then subjected to a sensitivity test by changing the soil type to high-activity clay (HAC).

Time-Dependent Emissions and Sequestration

While thermal processes such as fuel combustion lead to GHG emissions immediately, biological processes occur over long periods of time (Favoino and Hogg 2008). Biological processes include the sequestration of atmospheric carbon in woody biomass, GHG emissions from the gradual decomposition of soil organic matter, and new carbon incorporated into the soil as part of soil organic matter. These time-dependent emissions and sequestration events require that the timing be considered explicitly in the modeling.

The PAS 2050:2008 standard (BSI Group 2008) provides guidance on calculating the weighted average impact of carbon storage that may occur over a long product life cycle. The underlying principle states that the impact of carbon storage or uptake of atmospheric carbon should reflect the weighted average time of storage during the 100-year assessment period.

In applying this principle to the sequestration of atmospheric carbon in the woody biomass of perennial crops such as fruit trees, this study assumes that the carbon stored in the biomass is released at the end of the production life span (within the temporal boundary of the system) as the trees are cut down for replacement. The annual sequestration credit for biomass carbon is calculated according to the following equation from PAS 2050:2008, using estimates of the growth periods and biomass storage capacities of various tree species (Ministry of Agriculture and Land Reclamation 1998).

$$\Delta \mathrm{CO2e} = \frac{1}{A}\left(\frac{1}{L}\sum_{1}^{L}\sum_{1}^{G} B\right) D\frac{44}{12}, \tag{1}$$

where ΔCO2e is the CO_2 equivalent credit for annual biomass carbon stored per acre (kg), L is the total production life span (years), G is the growth period (years), B is the biomass carbon added annually by each tree of the given species (kg), D is the tree density (number of trees per acre), and A is the assessment period (100 years). The multiplier $\frac{44}{12}$ converts carbon to CO_2.

Although the PAS 2050:2008 standard currently excludes consideration of any changes to the carbon content of soils, this study applies the same basic principle of time-dependent carbon storage to model soil carbon sequestration, with the additional assumption that the carbon remains in the soil at the end of the production life span (it is reasonable to assume this if future land use practices are likely to conserve existing soil carbon). The sequestration credit for soil carbon is calculated according to the following equation based on the PAS 2050:2008 carbon sequestration model (BSI Group 2008) and the IPCC (2006) soil carbon model.

$$\Delta \mathrm{CO2e} = \frac{1}{A}\left(\frac{1}{L}\sum_{1}^{A}\sum_{1}^{M} S\right)\frac{44}{12}, \tag{2}$$

where ΔCO2e is the CO_2 equivalent credit for annual soil carbon stored per acre (kg), *M* is the the smaller of *L* and *T* (years), and *A* is the assessment period (100 years). The parameter *M* depends on two other parameters: *L* being the total production life span (years), and *T* being the soil carbon transition period (years).

In Equation 2, *S* is the long-term soil carbon in kilograms accumulated annually per acre during the transition period *T* as a function of a number of parameters (IPCC 2006).

$$S = F(c, m, s, lp, tp, cp, lc, tc, cc), \tag{3}$$

where *c* is the local climate zone, *m* is the moisture regime, *s* is the soil type, *lp* is the prior land-use category, *tp* is the prior tillage practice, *cp* is the prior level of carbon inputs added to the soil, *lc* is the current land-use category, *tc* is the current tillage practice, and *cc* is the current level of carbon inputs added to the soil. These parameters are based on IPCC (2006) classifications and the “current” values are specified for each farming system in Table 2. As previously specified, soil type is assumed to be LAC for all farming systems. The function *F* starts with the reference SOC stock for the soil type, climate zone and moisture regime, and then calculates the change in SOC as land use and management practices change from the “prior” to the “current” parameters. The function assumes that the soil carbon is at equilibrium before the change and again reaches equilibrium *T* years after the change, and is numerically implemented using the tier 1 data provided by IPCC (2006).

Nitrogen Inputs and Soil N_2O Emissions

The agricultural production data used in this study specify the exact quantities of manufactured nitrogen applied to the soil in a production year. This includes urea, calcium nitrate, calcium ammonium nitrate, and other forms of synthetic nitrogen, as well as organic nitrogen based on materials such as blood meal. In the case of bulky organic amendments such as compost and manure, the data specify the average quantities of the actual materials applied in each production year—these quantities are then converted into equivalent nitrogen for the purpose of calculating soil emissions. The nitrogen content of manure is between 0.5% and 1%, depending on the type of manure, after assuming that about 40% of the original nitrogen is lost on average in storage (Minnesota Department of Agriculture 1999). The nitrogen content of finished compost is about 1%, and 10% to 30% of this nitrogen will be available in the first year (Mangan et al. 2011). Since the production data is on an annualized basis and the same average quantity of compost is applied each year (for farming systems that use compost), the actual nitrogen available in any year comes from the compost applied in that year as well as through some of the nitrogen carried over from the compost applied in previous years. In total, it is assumed here that an average of 70% of the nitrogen content relative to each year's compost application is available in that year. Given the uncertainties inherent in the final estimate of nitrogen available annually from compost and the fairly broad use of compost across multiple crops, this estimate is subjected to a sensitivity test as described later.

The N_2O emissions are calculated using the IPCC tier 1 emission factors (IPCC 2006) for both direct and indirect emissions from soils, distinguishing between synthetic and organic nitrogen. This method assumes that an increase in available nitrogen enhances nitrification and denitrification rates in most soils, which then increase the direct production of N_2O. In addition, two indirect pathways are included: the volatilization of nitrogen as ammonia or oxides of nitrogen and the deposition of these gases and their products onto soils and water surfaces; and the leaching and runoff of applied nitrogen.

LCA Software and LCI Database

FoodCarbonScope (CleanMetrics 2011b), a web-based LCA software tool for food and beverage products, was used to perform the detailed cradle-to-farm gate GHG emissions modeling and analysis of all the farming systems. FoodCarbonScope supports all of the standards on which this study is based (BSI Group 2008; International Organization for Standardization 2006; IPCC 2006), allows flexible system boundary specifications, incorporates the necessary algorithms to calculate time-dependent emissions and sequestration in agricultural processes, and is able to analyze the impact of changes in land use and management practices.

FoodCarbonScope includes CarbonScopeData (CleanMetrics 2011a), which is a life cycle inventory (LCI) database with a strong emphasis on the food and agriculture sector in North America. CarbonScopeData provides the necessary LCI data to model a wide range of secondary processes in this study, including: production of fertilizers, pesticides and other material inputs; agricultural water production and distribution; transportation; fuel extraction, production and combustion; and electricity generation and transmission by grid region. Within this database, the cradle-to-grid electricity emissions for the California grid have been calculated based on electricity generation data (such as fuel mixes and transmission losses) from the eGRID database for the year 2005 (U.S. Environmental Protection Agency 2010) and power plant characteristics from the US U.S. Life Cycle Inventory Database ([USLCI] 2011). Emissions from the use of fuels such as gasoline, diesel and liquefied petroleum gas have been calculated based on the US LCI Database (USLCI 2011). Emissions from fertilizer production have been derived from International Fertilizer Industry Association (International Fertilizer Industry Association 2011). Since most pesticide production is based on proprietary commercial processes, emissions for the pesticide active ingredients are based on an average of production emissions for generic active ingredients and calculated using data from the Encyclopedia of Pest Management (Pimentel 2011).

FoodCarbonScope and CarbonScopeData have been used in other recent LCA studies of North American food systems (Hamerschlag and Venkat 2011; Venkat 2011), as well as in commercial LCA studies.

RESULTS AND DISCUSSION

Life Cycle Inventory Analysis

An inventory analysis is central to an LCA (Heijungs and Suh 2002) and has been performed using FoodCarbonScope in this study. This includes the construction of detailed models for each of the farming systems (conventional and organic) and alternative scenarios such as conversion from conventional to organic production. The models consist of linked unit processes for subsystems such as the production of inputs and transport, as well as various farm-level processes. Inventory analysis also includes the aggregation of GHG emissions from all sources within the spatial and temporal boundary of the farming system.

Table 3 illustrates a typical inventory table for the production of perennial crop, and Table 4 depicts a similar table for the production of an organic annual crop in transition. The inventory table includes only the specific inputs, outputs and other activities that are relevant to each farming system. The inventory data shown are for one year of production on one acre of land, with all greenhouse gases for each inventory item reported as a single CO_2e figure. Note that the emissions from the pumping of water are included in electricity use, and emissions from transport are included in the emissions figures for all material inputs delivered to the farm. All pesticide quantities are for the active ingredients.

TABLE 3 Life cycle inventory for the production of a conventional perennial crop (907 kg of almonds per acre per year)

Input, output or other activity	Quantity	Units	Cradle-to-Farm gateGHG emissions (kg CO_2e)
Water—pumped	4521391	L	0
Gasoline	38.335	L	97.93
Diesel	43.3681	L	139.98
Electricity—California grid	1364.98	kWh	661.66
Insecticide	0.1317	kg	3.95
Herbicide	2.2256	kg	79.75
Fungicide—other than sulfur	2.9847	kg	76.74
Rodenticide	0.0034	kg	0.1
Fungicide—sulfur	30.8446	kg	241.26
Pesticide formulation—miscible oil	7.465	kg	67.09
Pesticide formulation—wettable powder	5.103	kg	3.93
Potassium	90.7194	kg	70.04
Urea nitrogen	90.7194	kg	127.76
Zinc	1.134	kg	4.55
Boron	0.7938	kg	0.12
Custom work	729	$	28.29
Pesticide—mineral oil	3.0274	kg	5.64
Crop Establishment (amortized)			0.27
Soil N_2O from nitrogen/urea			562.89
Soil CO_2 from urea/lime			145.15
Carbon incorporated in perennial crop			−68.04
TOTAL			2249.08

Comparison of Organic and Conventional Farming Systems

The comparison of GHG emissions for conventional and organic production is on the basis of one kilograms of product. Table 5 summarizes the aggregate cradle-to-farm gate GHG emissions for steady-state conventional, steady-state organic and transitional organic farming systems. The two right-most columns compare the organic and transitional organic systems with the conventional system, with negative percentages indicating that the organic system produced lower emissions. Figure 2 illustrates the same results graphically.

Of the 12 crop products compared in this study, steady-state organic production has lower GHG emissions per product unit in only five cases. Steady-state conventional production has the lower emissions in the other seven cases. The average emissions from organic production are higher by 50.5%. This average is significantly skewed by the extreme differences in the results for walnuts; after excluding this one data point as an outlier, the average emissions for organic production are higher by 10.6%.

TABLE 4 Life cycle inventory for the production of an organic annual crop in transition (8,505 kg of leaf lettuce per acre per year)

Input, output or other activity	Quantity	Units	Cradle-to-farm gateGHG emissions (kg CO_2e)
Water—pumped	1746901	L	0
Gasoline	22.5166	L	57.52
Diesel	238.638	L	770.23
Electricity—California grid	527.379	kWh	255.64
Insecticide	0.4037	kg	12.11
Pesticide formulation—miscible oil	1.1343	kg	10.2
Pesticide formulation—wettable powder	0.4536	kg	0.35
Compost	2267.99	kg	160.34
Blood, meat and bone meal nitrogen	26.5354	kg	29.1
Manure—chicken	453.597	kg	9.22
Other organic nitrogen	4.6539	kg	21.48
Gypsum	453.597	kg	125.5
Seed	184.95	$	286.67
Custom work	5033	$	195.28
Soil N_2O from nitrogen/urea			347.06
Soil CO_2/N_2O emissions or soil carbon sequestration due to land use or management changes			−155.73
TOTAL			2124.97

The reasons for the relatively poor performance of steady-state organic production vary in each case, but the primary reasons can be summarized as:

- Organic farming sometimes produces yields that are lower than comparable conventional farming. In some of the extreme cases where organic production performs poorly, the yields are in the range of 20% to 80% of the conventional yield.
- In each of the seven cases where conventional production performs better, organic production generates significantly higher emissions per product unit from on-farm energy use.
- Some organic farming systems have additional GHG emissions from the manufacture of sulfur used as fungicide and the application of lime.
- A few organic farming systems use large quantities of compost (e.g., 9071 kg of compost per acre annually to produce 725 kg of almonds, and 1360 kg of compost to produce 453 kg of walnuts). Even though the production and delivery of compost generates fairly low GHG emissions per unit (about 0.07 kg CO_2e/kg), the large quantities involved contribute significant additional emissions per product unit.
- Soil N_2O emissions from nitrogen fertilizer use are similar for conventional and organic farming, with emissions for conventional production modestly higher in some cases.

TABLE 5 Cradle-to-farm gate GHG emissions for conventional (steady-state), organic (steady-state), and organic (transitional) production

Crop product	Conventional (kg CO_2e/kg product)	Organic (kg CO_2e/kg product)	Organic-transitional (kg CO_2e/kg product)	Organic vs. conventional (% decrease or increase)	Organic-transitional vs. conventional (% decrease or increase)
Blueberries	0.829	0.723	0.723	−12.8	−12.8
Apples #1	0.188	0.267	0.245	42.1	30.6
Apples #2	0.108	0.176	0.008	63.1	−93.0
Wine grapes #1	0.272	0.244	0.046	−10.4	−83.1
Wine grapes #2	0.205	0.179	0.177	−12.5	−13.8
Raisin grapes	0.667	0.700	0.674	4.9	1.0
Strawberries	0.337	0.234	0.218	−30.5	−35.2
Alfalfa for hay	0.132	0.086	0.084	−34.5	−36.1
Almonds	2.479	3.771	3.206	52.1	29.3
Walnuts	0.499	2.942	1.970	489.1	294.4
Broccoli	0.353	0.409	0.310	15.8	−12.3
Lettuce	0.192	0.268	0.250	39.8	30.2
Average				50.5	8.3
Average (excl. walnuts)				10.6	−17.7

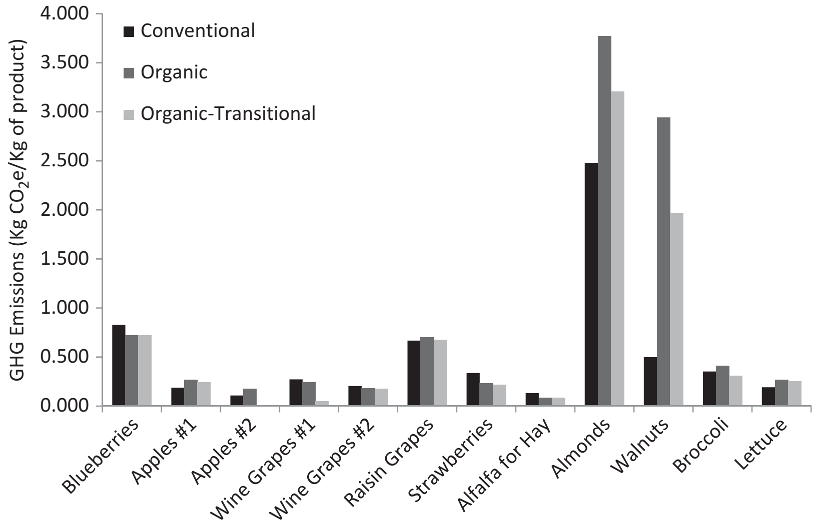

FIGURE 2 Cradle-to-farm gate GHG emissions for conventional (steady-state), organic (steady-state) and organic (transitional) production.

- Emissions from the manufacture and transport of synthetic fertilizers and pesticides used in conventional farming are not large enough in many cases to overcome the additional emissions per kilogram of product in organic farming.

Two of the key reasons noted here—lower yields and higher on-farm energy use per product unit—have some support in the recent literature comparing organic and conventional production. Lower yields have been identified in other LCA studies and meta-analyses (Williams et al. 2006; Bos et al. 2007; Mondelaers et al. 2009; Gomiero et al. 2008; MacRae et al. 2010; De Backer et al. 2009) as a primary disadvantage of organic farming methods at present. While organic systems may use lower energy per land unit, comparisons per unit of food output favor organics less strongly due to the lower yields (Gomiero et al. 2008; MacRae et al. 2010; Mondelaers et al. 2009).

Looking specifically at on-farm energy use, Lynch et al. (2011) found energy use to be higher in organic fruit production (including specifically apples) compared to conventional production, but lower for organic vegetables. Our results are consistent with Lynch et al. (2011) for fruits but differ for the two vegetables included in this study: Both broccoli and lettuce consume more on-farm energy in organic production. This characteristic is fairly uniform across all crop products considered in this study, possibly due to systematically higher levels of mechanical labor used in these California-based organic farming systems. Mondelaers et al. (2009) concluded from their meta-analysis that higher fuel combustion from mechanical weeding in organic farming offsets the emissions reduced by the avoided manufacture of synthetic inputs, which supports our findings.

Transitional organic production fares better than steady-state organic production. It generates lower GHG emissions per product unit than steady-state conventional production in seven cases, and 17.7% lower emissions on average (excluding walnuts). Transitional organic production also generates lower emissions than steady-state organic production in all but one case where they generate equal emissions and 22.3% lower emissions on average—this difference essentially quantifies the overall impact of soil carbon sequestration. Transitional organic production delivers considerably improved environmental performance in three cases (apples #2, almonds and walnuts) where the organic yield per acre is low and therefore each kilogram of product gets a higher carbon sequestration credit than in other cases. These results demonstrate, within the limitations of the production data and the IPCC (2006) tier 1 soil carbon model, that conversion from conventional to organic farming may offer significant GHG reduction opportunities.

In addition to avoiding the use of synthetic inputs, organic production may differ from conventional production in the tillage practice and the level of organic carbon added to the soil as shown in Table 2. Of these two variables, the carbon added to the soil is the primary differentiator between the two production methods for the farming systems included in this study, particularly where the organic production uses the "high carbon–with manure" regime. This suggests that some nonorganic farming systems may be able to improve their environmental performance by adopting similar practices to increase SOC stocks without entirely switching to organic methods.

The results presented here also highlight the need for a more fine-grained assessment of soil carbon dynamics than possible using the IPCC tier 1 model. Such an assessment would take into account the exact amounts and timing of organic carbon added to the soil in addition to all the other factors considered in this study.

Sensitivity Analysis

Sensitivity analysis is a necessary part of any modeling endeavor. It is used to test the robustness of conclusions to uncertainties in assumptions (Sterman 2000). Of the different types of sensitivities that models exhibit, numerical sensitivity to parametric assumptions is important for LCA models and is routinely tested in LCA studies (Dalgaard et al. 2008; Pelletier et al. 2010).

Figure 3 shows the GHG emissions response of the models used in this study to changes in the assumed transport distances for material inputs delivered to the farms, including all fertilizers, soil amendments and pesticides. As noted previously, the baseline scenarios assume that all synthetic inputs used in conventional production are transported 1,800 km to

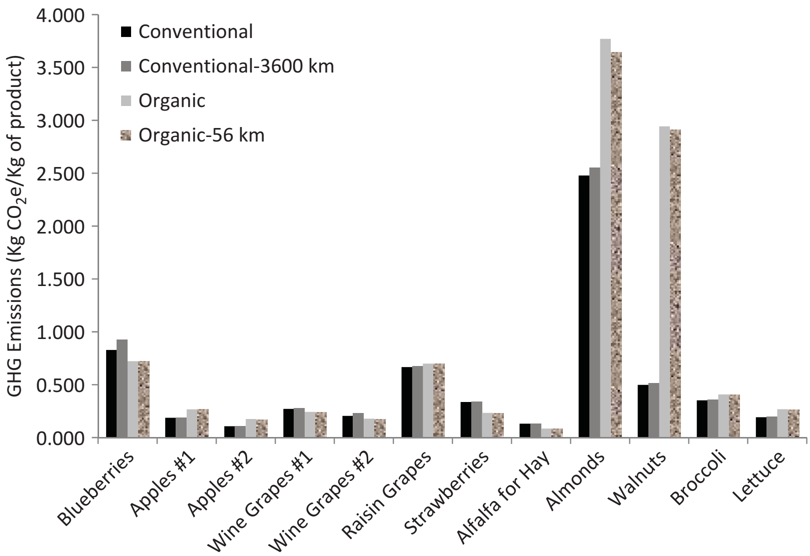

FIGURE 3 Cradle-to-farm gate GHG emissions for conventional (steady-state) and organic (steady-state) production with variable distances for transport of inputs to the farm (color figure available online).

the farm. Organic inputs such as compost and manure are assumed to be transported 112 km to the farm. Figure 3 depicts two additional scenarios: conventional production with the transport distance doubled to 3600 km; and organic production with the transport distance halved to 56 km. The cradle-to-farm gate GHG emissions vary by less than 4% in all organic systems and in 10 out of 12 conventional systems. The emissions are higher by about 12% in two conventional systems (blueberries and wine grapes #2). This sensitivity test shows that the models are robust and largely insensitive to the transport distance assumptions and any uncertainties in these assumptions are unlikely to change the general nature of the overall results.

Figure 4 uses the transitional organic almond system as a test case to examine the sensitivity of the GHG emissions to changes in the production life span and the transition period. The baseline scenarios assume that the production life span is 30 years and the transition period is 20 years. Figure 4 shows effect of varying the production life span from 20 to 35 years, and the transition period from 15 to 30 years. The model is quite insensitive to the transition period given a fixed soil carbon sequestration capacity, with the total emissions decreasing only slightly as the transition period is shortened. It is relatively more sensitive to variations in the production life span because a fixed amount of carbon sequestration capacity must be allocated to all of the production during the entire life span. Overall, the cradle-to-farm gate GHG emissions vary by less than 8% (relative to the baseline emissions)

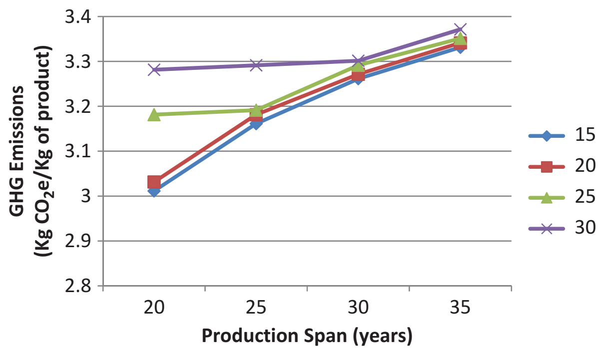

FIGURE 4 Cradle-to-farm gate GHG emissions for transitional organic almond production on low-activity clay soil, as a function of the production life span (20–35 years) and the transition period (15–30 years) (color figure available online).

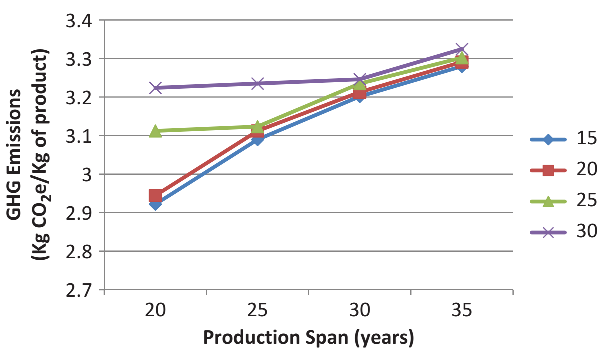

FIGURE 5 Cradle-to-farm gate GHG emissions for transitional organic almond production on high-activity clay soil, as a function of the production life span (20–35 years) and the transition period (15–30 years) (color figure available online).

in this sensitivity test. Note that when the transition period exceeds the production life span, the lower limit for the emissions is determined by the life span.

The soil type was assumed to be LAC for all farming systems. Figure 5 tests this assumption by changing from LAC to HAC soil and using the same test methodology as Figure 4. HAC soil provides about 9% higher soil carbon sequestration capacity for the warm temperate/moist zone where the almond crops are grown (IPCC 2006). This translates to less than a 3% decrease in cradle-to-farm gate GHG emissions because soil carbon is not the dominant contributor to the GHG emissions. These last two sensitivity tests confirm the robustness of the LCA models with respect to assumptions of production and transition time periods.

The final sensitivity test considers the uncertainty in the estimate of nitrogen available from regular compost application, using as test cases two organic crops (almonds and walnuts) that use the largest quantities of compost relative to their yield. As described earlier, nitrogen available annually from all sources is estimated to be 0.7% of the weight of compost applied each year. If this estimate is varied between 0.5% and 0.9% (±28.6% from baseline), cradle-to-farm gate GHG emissions vary by less than 4.6% in the case of almonds and less than 1.75% in the case of walnuts. Other crops exhibit even less sensitivity to this uncertainty. While a more accurate and refined estimate of compost nitrogen availability will be preferable, it is clear that fairly significant variations in this estimate will not materially change the results.

CONCLUSIONS

This study compares the environmental impacts of 12 distinct crop products that are grown in the agricultural regions of California using both conventional and organic methods. Using publicly available agricultural production data for these crops, it applies standards-based LCA techniques to compare the cradle-to-farm gate GHG emissions per kilogram of each crop product grown using each production method. In addition to analyzing baseline steady-state scenarios in which the SOC stock is at equilibrium in both the conventional and organic systems, this study models a hypothetical scenario of converting each conventional farming system to a corresponding organic system and examines the impact of soil carbon sequestration during the transition. In order to accomplish this last part, the study establishes the climate zone, moisture regime, soil type, land use, and management practices for each of the conventional and organic farming systems.

Of the 12 crop products, steady-state organic production has lower GHG emissions in only five cases. Steady-state conventional production has the lower emissions in the other seven cases. Average emissions for steady-state organic production are higher by 10.6% (excluding walnuts as an outlier). The reasons for this vary, including: lower yields and higher on-farm energy use in organic farming, the production and delivery of large quantities of compost in some organic systems, and the fact that emissions from the manufacture of synthetic fertilizers and pesticides used in conventional farming are not large enough to offset the additional emissions in organic farming.

Transitional organic production fares better than steady-state organic production. It generates lower GHG emissions than steady-state conventional production in seven cases, and 17.7% lower emissions on average (excluding walnuts). It also generates lower emissions than steady-state organic production in all but one case where they generate equal emissions. Soil carbon sequestration drives the emissions for transitional organic production lower by an average of 22.3% compared to steady-state organic production. The results demonstrate, within the limitations of the data and the modeling, that converting additional cropland to organic production over the next few decades may offer significant GHG reduction opportunities by way of increasing the SOC stocks during the transition. If those higher levels of carbon stocks can be maintained in the soil over the long term (as assumed in this study), then converting to organic production may indeed prove to be an important tool in the mitigation of climate change. The results also suggest the possibility that some nonorganic farming systems may be able to improve their environmental performance by adopting practices to increase soil carbon stocks without entirely switching to organic methods.

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