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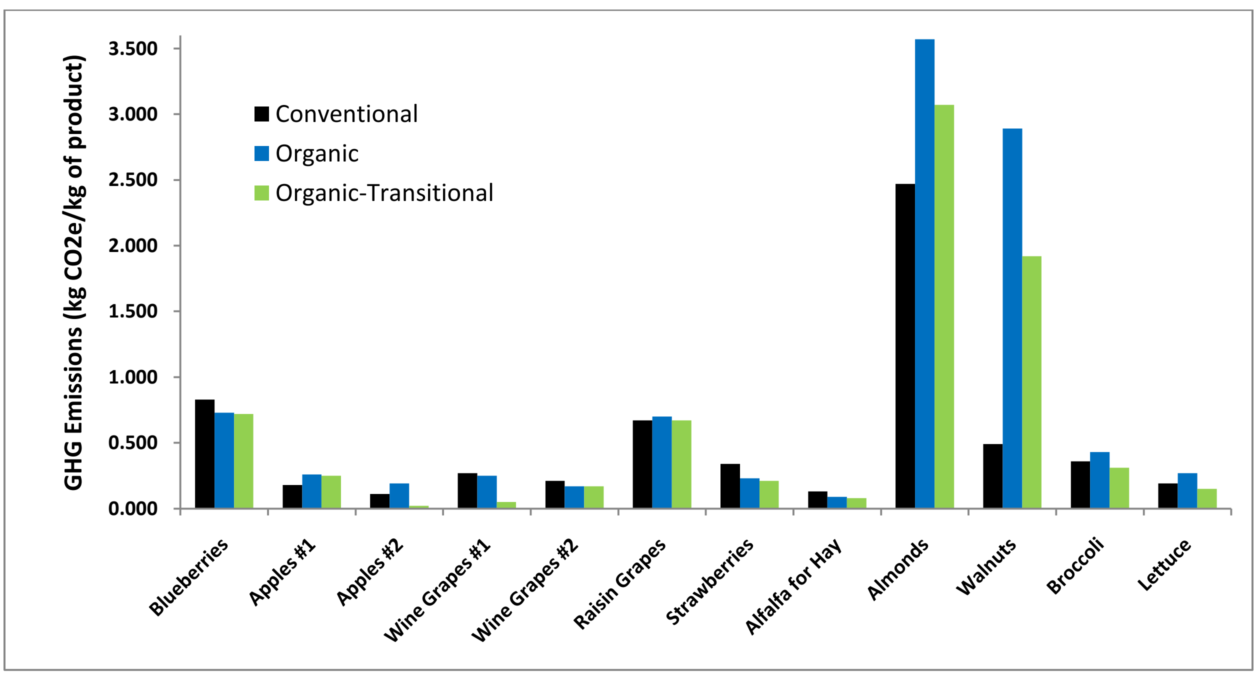
Comparison of Twelve Organic and Conventional Farming Systems: A Life Cycle Greenhouse Gas Emissions Perspective

Kumar Venkat
CleanMetrics Corp.

SUMMARY

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 (LCA) techniques, using the FoodCarbonScope™ software, to compare the cradle-to-farm gate greenhouse gas (GHG) emissions of 12 crop products that are grown in the agricultural regions of California under 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 GHG emissions than conventional production in 7 out of the 12 cases. Transitional organic production performs significantly better, generating higher emissions than conventional production in just 3 cases. 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. Non-organic systems could also improve their environmental performance by adopting management practices to increase soil carbon stocks.



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

KUMAR VENKAT[1]

CleanMetrics Corp., Portland, Oregon

ABSTRACT

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 (LCA) techniques to compare the cradle-to-farm gate greenhouse gas (GHG) emissions of 12 crop products that are grown in the agricultural regions of 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 GHG emissions than conventional production in 7 out of the 12 cases. Transitional organic production performs significantly better, generating higher emissions than conventional production in just 3 cases. 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. Non-organic systems could also improve their environmental performance by adopting management practices to increase soil carbon stocks.

KEYWORDS: life cycle assessment, LCA, greenhouse gas emissions, GHG emissions, organic agriculture, soil carbon sequestration

INTRODUCTION

The global market for organic food and drinks was estimated to approach \$60 billion in 2010 (Triple Pundit, 2010). Although the market share is still very small – about 3% of food sales in the United States (USDA, 2009) – the organic segment has experienced rapid growth with global sales tripling in the last 10 years. 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 (CO2e) per year mainly through soil carbon sequestration and climate change targets cannot be met without realizing a substantial part of this potential (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.

[1] Address correspondence to Kumar Venkat, CleanMetrics Corp., 4804 NW Bethany Blvd., Suite I2 #191, Portland, OR 97229, USA. E-mail: kvenkat@cleanmetrics.com

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 (ISO, 2006). However, such comparative LCA studies of organic and conventional farming methods are relatively few and limited in the literature.

Williams et al. (2006) analyzed the life cycle impacts of four crops grown conventionally and organically in England and Wales. They found that organic wheat production used 27% less energy compared with non-organic, 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% to 200% higher in organic systems due to lower yields and additional overheads such as cover crops.

Meisterling et al. (2009) compared organic and conventional wheat production and delivery in the United States using representative national data. They found a relatively minor GHG emissions advantage for organic production which vanished as the transport distance to market increased.

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) used hypothetical organic farming models for four major field crops and compared them with conventional production in Canada. They found that organic production would generate 23% lower emissions than conventional production, without including soil carbon sequestration. 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.

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. 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.

Each of these studies is specific to a particular geographical region, so it is not straight-forward to apply the results to other regions. Two of these 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 carbon were not included in all but one 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 (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.

The motivation for the present study was to overcome some of the limitations in the existing literature comparing the impacts of organic and conventional farming methods. In particular, the goals of this study were to: (a) develop a robust 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, 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 kg 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.

METHODS

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 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,	6350.36	1994	UCD, 1994a
Apples #2	Conventional	Granny Smith	18852.63	2001	UCD, 2001
Apples #2	Organic	Granny Smith,	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

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

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
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

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 (N2O) emissions due to the use of synthetic and organic nitrogen fertilizers and crop residues; carbon dioxide (CO2) emissions due to the use of urea and lime; and CO2 and N2O 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 one kg of product. All GHG emissions are reported in kg of CO2e.

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 LPG, 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.

Organic fertilizers and soil amendments such as compost and manure are derived from waste outputs generated by other systems. These inputs are assumed to enter the farming systems without any environmental burdens for manufacture. This approach 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 waste to a recycling facility, and then any subsequent transport and processing of that material are included within other systems that use the material in some form.

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 300 km distance. 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 soil organic carbon is at a spatially averaged equilibrium and is therefore neither increasing nor decreasing for the purposes of calculating net soil-derived GHG emissions (IPCC, 2006; Smith et al., 2008; Phetteplace et al., 2001). 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.

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 soil organic carbon 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 N2O 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 N2O 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 in this study: 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.

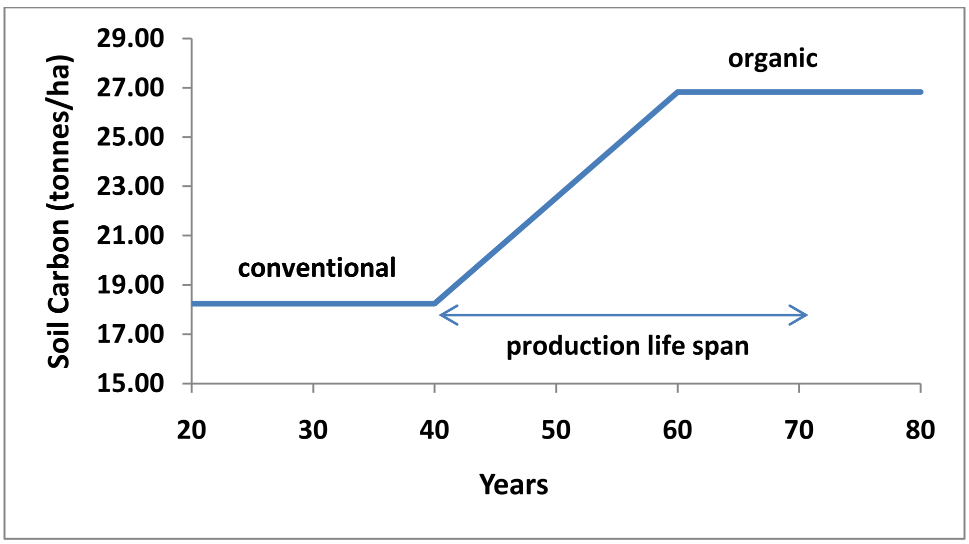


Figure 1 Soil carbon profile over a 20 year transition period in a typical conversion from conventional to organic production, based on IPCC (2006)

Figure 1 illustrates the soil carbon profile in a typical transition from conventional to organic production, where the transition starts in year 40 which is the first year of production for the organic farming system. The transition ends in year 60 and the organic production ends in year 70 in this example.

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 carbon to reach steady state again – is assumed to be nominally 20 years, 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, using estimates of the growth periods and biomass storage capacities of various tree species (MAOLR, 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 $\Delta\mathrm{CO2e} =$ CO2 equivalent credit for annual biomass carbon stored per acre (kg), L = total production life span (years), G = growth period (years), B = biomass carbon added annually by each tree of the given species (kg), D = tree density (number of trees per acre), and A = assessment period (100 years). The multiplier $\frac{44}{12}$ converts carbon to CO2.

Although the PAS 2050:2008 standard currently excludes consideration 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.

$$\Delta \mathrm{CO2e} = \frac{1}{A}\left(\frac{1}{L}\sum_1^A \sum_1^M S\right) \frac{44}{12} \tag{2}$$

where $\Delta CO2e =$ CO2 equivalent credit for annual soil carbon stored per acre (kg), *L* = total production life span (years), *T* = soil carbon transition period (years), *M* = the smaller of *L* and *T* (years), and *A* = assessment period (100 years).

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

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

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 soil organic carbon stock for the soil type, climate zone and moisture regime, and then calculates the change in soil carbon 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).

LCA Software

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; ISO, 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. 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 and combustion; and electricity generation and transmission by grid region.

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 CO2e 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 Gate GHG Emissions (kg CO2e)
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 N2O from nitrogen/urea			562.89
Soil CO2 from urea/lime			145.15
Carbon incorporated in perennial crop			-68.04
TOTAL			2249.08

Table 4 Life cycle inventory for the production of an organic annual crop in transition (8505 kg of leaf lettuce per acre per year)

Input, Output or Other Activity	Quantity	Units	Cradle-to-Farm Gate GHG Emissions (kg CO2e)
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	123.54
Blood, meat and bone meal nitrogen	26.5354	kg	29.1
Manure - chicken	453.597	kg	24.71
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 N2O from nitrogen/urea			347.06
Soil CO2/N2O emissions or soil carbon sequestration due to land use or management changes			-155.73
TOTAL			2103.66

Comparison of Organic and Conventional Farming Systems

The comparison of GHG emissions for conventional and organic production is on the basis of one kg 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 in only five cases. Steady-state conventional production has the lower emissions in the other seven cases. The reasons for this 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.

- Organic farming generates significantly higher emissions from on-farm energy use in some cases.
- Some organic farming systems have additional GHG emissions from the manufacture of sulfur used as fungicide and the application of lime.
- Transport of large quantities of compost or manure (for example, 9000 kg of compost annually for one acre of almond production, or 1800 kg of organic fertilizers for one acre of walnut production), even when transported just 300 km, can produce significant emissions.
- Soil N2O emissions from nitrogen fertilizer use are similar for conventional and organic farming, with emissions for conventional production modestly higher in some cases.
- 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 kg of product in organic farming.

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

Crop Product	Conventional (kg CO2e/ kg product)	Organic (kg CO2e/ kg product)	Organic-Transitional (kg CO2e/ kg product)	Organic vs. Conventional (% decrease or increase)	Organic-Transitional vs. Conventional (% decrease or increase)
Blueberries	0.830	0.730	0.720	-12.05	-13.25
Apples #1	0.180	0.260	0.250	44.44	38.89
Apples #2	0.110	0.190	0.020	72.73	-81.82
Wine Grapes #1	0.270	0.250	0.050	-7.41	-81.48
Wine Grapes #2	0.210	0.170	0.170	-19.05	-19.05
Raisin Grapes	0.670	0.700	0.670	4.48	0.00
Strawberries	0.340	0.230	0.210	-32.35	-38.24
Alfalfa for Hay	0.130	0.090	0.080	-30.77	-38.46
Almonds	2.470	3.570	3.071	44.53	24.35
Walnuts	0.490	2.890	1.920	489.80	291.84
Broccoli	0.360	0.430	0.310	19.44	-13.89
Lettuce	0.190	0.270	0.150	42.11	-21.05

Transitional organic production fares much better than steady-state organic production. It generates higher GHG emissions than steady-state conventional production in just three cases, and lower emissions than steady-state organic production in all but one case where they generate equal emissions. Transitional organic production delivers significantly improved environmental performance in three cases (apples #2, almonds and walnuts) where the organic yield per acre is low and therefore each kg 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 non-organic farming systems may be able to improve their environmental performance by adopting similar practices to increase soil carbon 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.

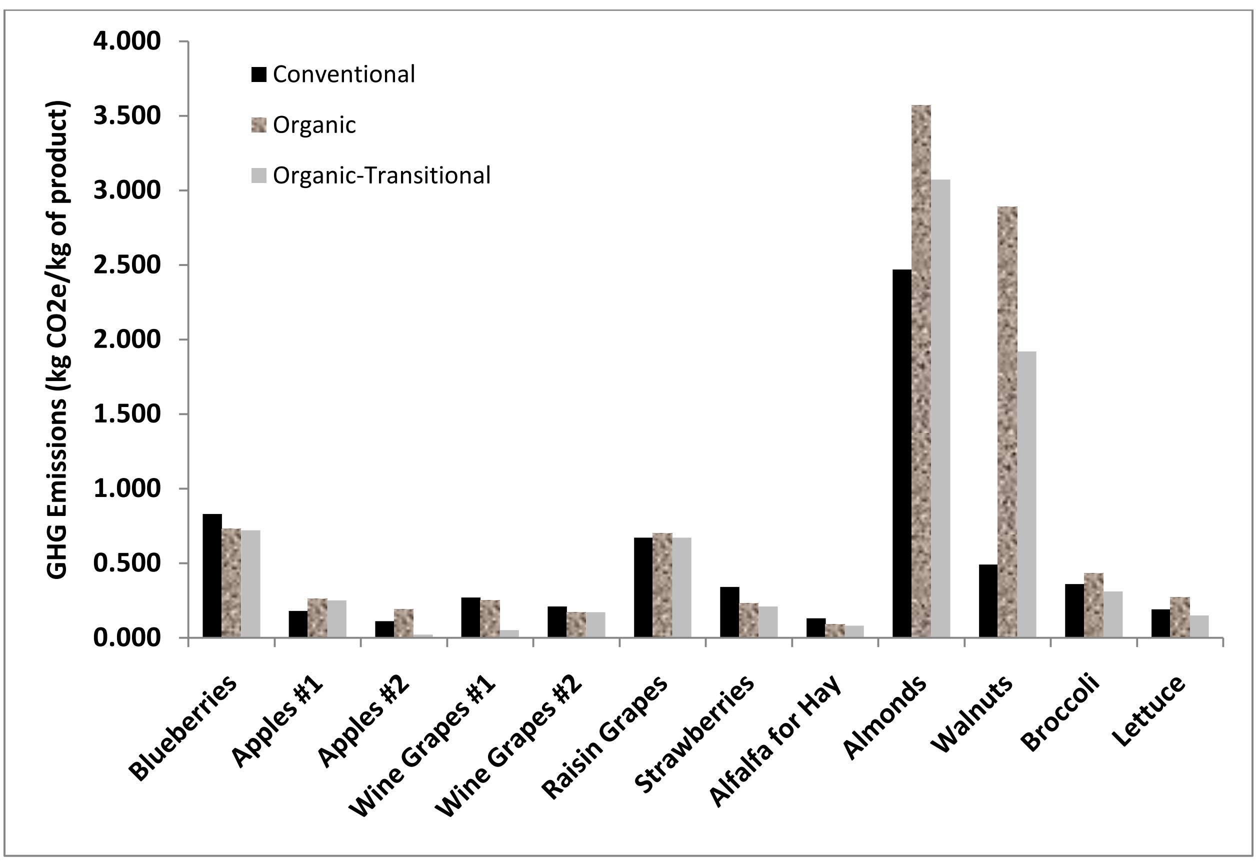


Figure 2 Cradle-to-farm gate GHG emissions for conventional (steady-state), organic (steady-state) and organic (transitional) production.

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 1800 km to the farm. Organic inputs such as compost and manure are assumed to be transported 300 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 150 km. Only organic almonds and organic walnuts demonstrate any significant sensitivity to the distance assumption because of the large quantities of compost used in these two farming systems. In terms of percentages, cradle-to-farm gate GHG emissions vary by less than 5% in most cases and by less than 12% in all cases.

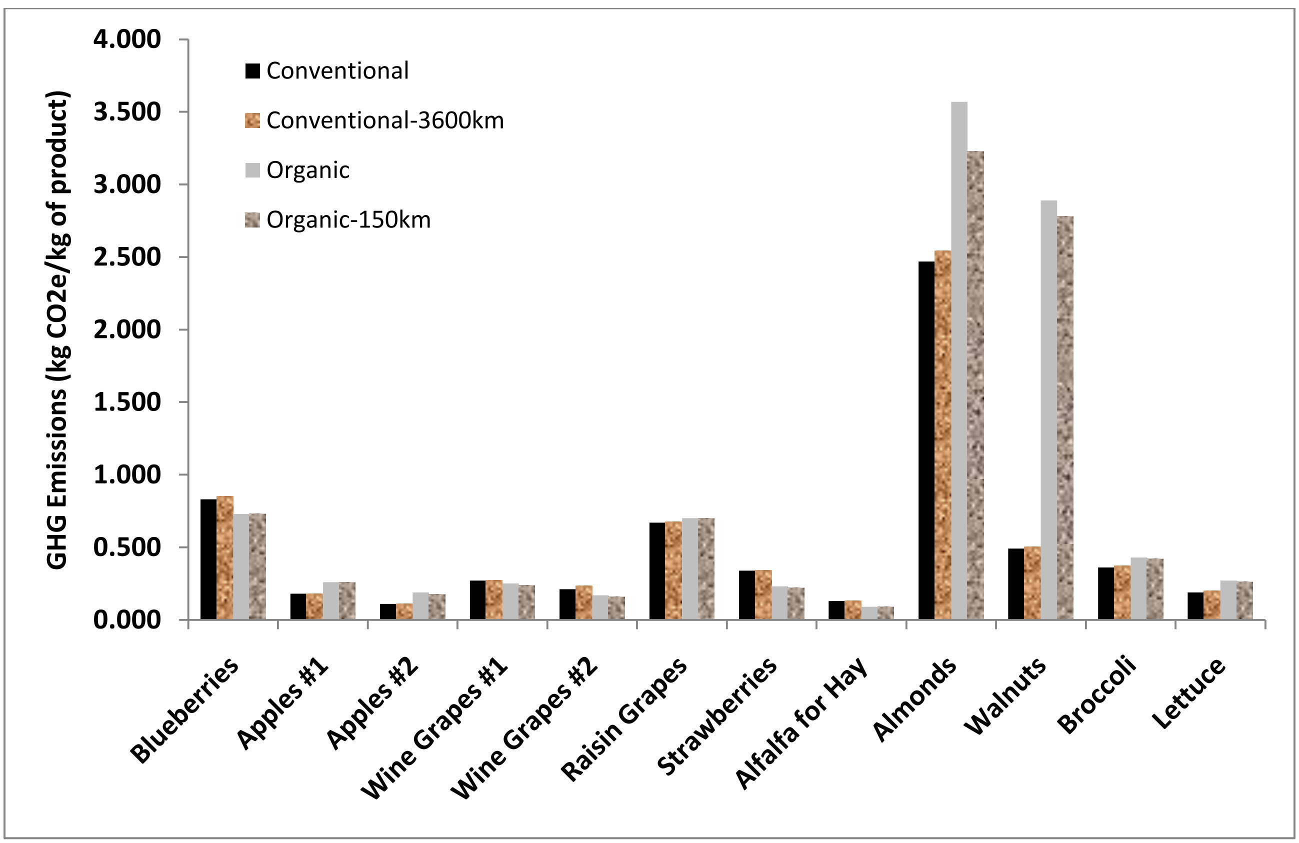


Figure 3 Cradle-to-farm gate GHG emissions for conventional (steady-state) and organic (steady-state) production with variable distances for transport of inputs to the farm.

It is clear from this sensitivity test 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 years to 35 years, and the transition period from 15 years 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 9% (relative to the baseline emissions) 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.

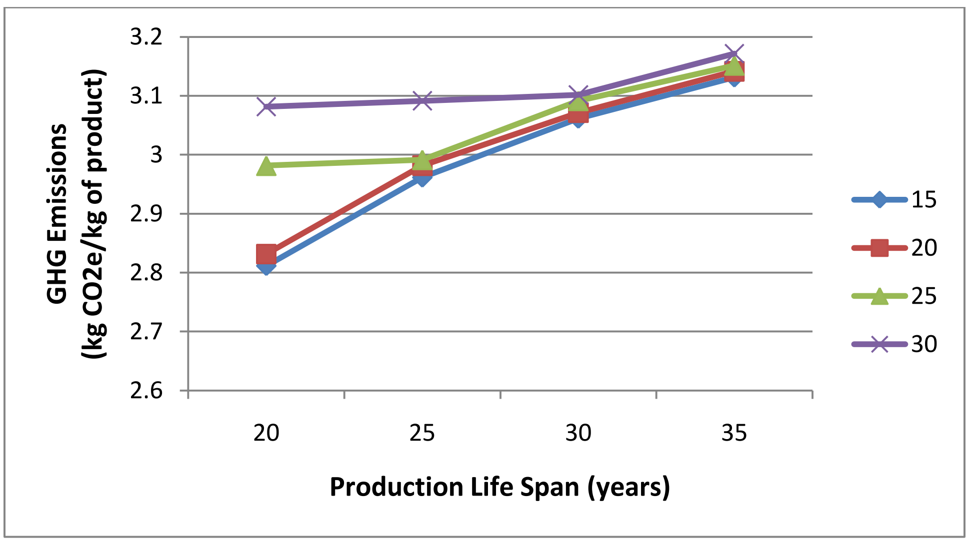


Figure 4 Cradle-to-farm gate GHG emissions for transitional organic almond production on low-activity clay soil, as a function of the production life span and the transition period.

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 2% 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 again confirm the robustness of the LCA models with respect to parametric assumptions.

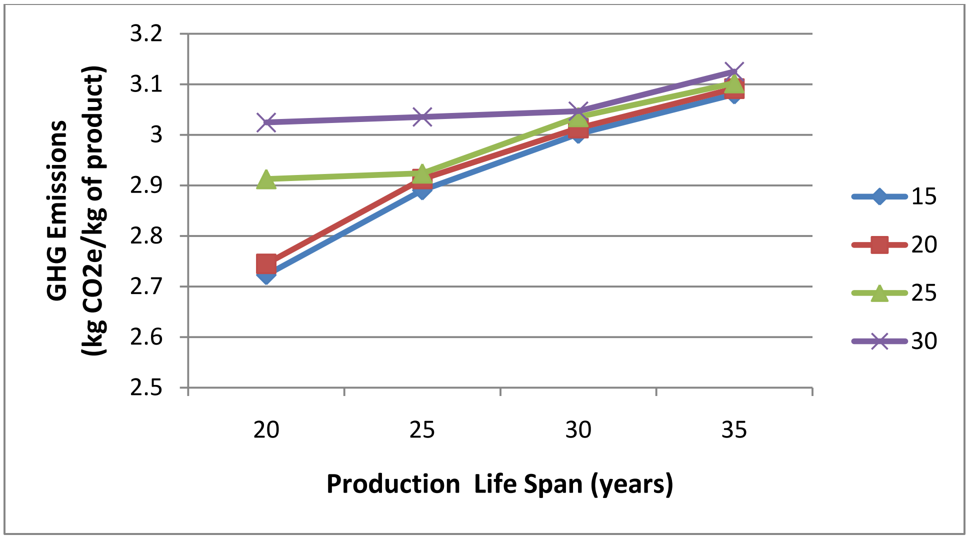


Figure 5 Cradle-to-farm gate GHG emissions for transitional organic almond production on high-activity clay soil, as a function of the production life span and the transition period.

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 kg of each crop product grown using each production method. In addition to analyzing baseline steady-state scenarios in which the soil organic carbon 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. The reasons for this vary, including: lower yields and higher on-farm energy use in organic farming, the need for local transport of large quantities of compost or manure to organic farms, 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 much better than steady-state organic production. It generates higher GHG emissions than steady-state conventional production in just three cases, and lower emissions than steady-state organic production in all but one case where they generate equal emissions. 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 soil organic carbon 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 non-organic 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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