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Life-Cycle Assessment in Agricultural Systems

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Consumers, and society in general, are becoming more aware of the environmental impacts of our manufacturing and agriculture. This publication introduces an environmental impact analysis tool called Life-Cycle Assessment (LCA). LCA can be used to identify and quantify environmental impacts so that they may be more efficiently addressed. The first sections explain how LCA can be used to evaluate agricultural systems, suggesting ways to interpret and apply LCA findings to one's own farming system. The third discusses LCA applications in farming and gives an overview of a well-known LCA agricultural case study from Sweden that compares organic and conventional milk production. The fourth section describes several recent and ongoing LCA studies for almonds, wine grapes, wine, honey, tomatoes, and corn/bean systems. Useful resources are listed in the appendices.

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Introduction

The agriculture sector faces mounting pressure to increase productivity, reduce costs while maintaining product quality, and respond to regulatory and market shifts. This publication discusses Life-Cycle Assessment (LCA), a tool to help growers and policymakers understand the full environmental impacts of an agricultural production system, identifying ways growers can improve overall efficiency. Use of this tool may open up new "green marketing" opportunities and even lead to reduced overall costs through better utilization of energy, equipment, and agrochemical resources.

LCA is defined by the International Organization for Standardization (ISO) as a tool to analyze the potential environmental impacts of products at all stages in their life cycle. Products can be goods or services, ranging from electricity to consumables to waste-management strategies (ISO Standards). LCA examines a product's entire life cycle beginning with extraction of natural resources and continuing through production of materials, product parts, and the product itself, to the use of the product, packaging, and recycling or final disposal (see Figure 1). Materials transport and energy production within the supply chain are tracked throughout the life cycle and often contribute significantly to the overall environmental impact.

LCA is more than a carbon footprinting tool because it attempts to quantify all environmental impacts associated with the life cycle of a particular product. These impacts include use of natural resources and land, as well as the release of environmental contaminants to the soil, air, and water. LCA identifies ways that various practices contribute to the overall environmental impact of the production system. The assessment illuminates strengths as well as opportunities for improvement.

Types of Life-Cycle Assessment and How They Work

Life cycle assessment is used for a wide variety of disciplines and purposes. Major corporations all over the world are undertaking LCA (in-house or third-party studies) to evaluate the environmental impacts of processes associated with a particular product. Certification of these products for LCA-based labels can help compare the relative environmental impacts of competing products.

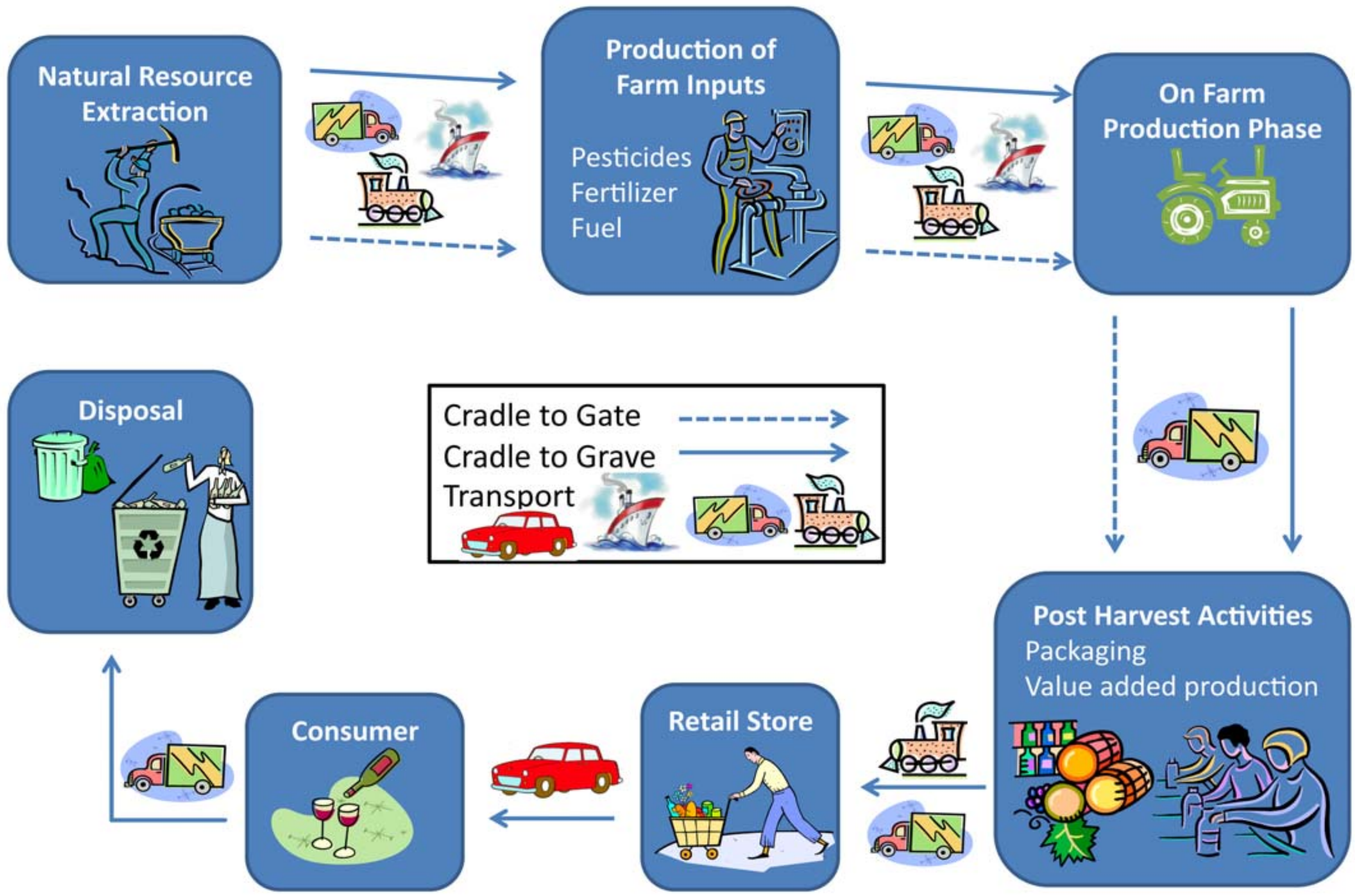


Figure 1. Life-Cycle Assessment Phases, Cradle-to-Gate and Cradle-to-Grave
Figure 1 depicts a simplified life-cycle assessment (LCA) of wine. Environmental impacts are quantified from all life-cycle phases. These phases include raw material extraction, on-farm production methods (see Figure 3, page 11), and production and use of materials like fertilizers, pesticides, and fuel. Depending on the goal of the LCA, the assessment can end at wine grape delivery to the winery (cradle-to-gate) or it can be followed through wine production, consumption, and disposal of the wine bottle (cradle-to-grave). See Table 1. Environmental impacts related to transport at all life-cycle phases are tracked as well.

LCA also has major roles in integrated waste management and pollution studies.

The objectives of a particular LCA will determine the appropriate method to use. LCA methods can be determined by asking three questions:

1) Are you evaluating a single product or process, or are you evaluating and comparing multiple products and processes?

2) Where are the boundaries that define the beginning and the end of the system?

3) Is it your objective to evaluate the current state of the system or is it to predict the impact of alternative production methods? A brief comparison and definition of different LCA methods are presented in Table 1.

A life-cycle cost analysis can be completed alongside an environmental impact LCA in order to consider the financial costs as well as the environmental impacts of each alternative. Life-cycle cost analysis accounts for all costs incurred during the lifetime of a product. Costs include those associated with purchases, production, operation and maintenance, labor, disposal, and occasionally externalities such as pollution damage costs incurred by third parties. Consideration is given for who carries the financial burden (the producer, the user, or a third party), as well as whether the costs are near, in the future, or spread out over time (for example, installing solar panels has a high initial expense but energy costs are reduced and over the long-term can be cost-saving).

Table 1. Life-Cycle Assessment Methods	
The LCA method is determined based on the number of production chains or systems being evaluated (comparative or stand-alone?), the scope (cradle-to-gate or cradle-to-grave?), and the objectives of the study (attributional or consequential?). Multiple methods in combination may be appropriate for a single LCA. For example, a cradle-to-grave LCA can be either stand-alone or comparative, depending on the number of systems evaluated. Definitions are given here, as are examples for industrial manufacture and for agriculture.	
1) Is the purpose of the assessment to evaluate a single product/process or to compare multiple products and processes?	
Stand-Alone LCA	**Comparative LCA**
This LCA method analyzes a single product to identify the life-cycle components, known as "hotspots," that contribute most to the environmental impacts.	This LCA method determines the benefits and trade-offs between two or more comparable products.
Industrial Example: Which life-cycle phase (bottle manufacturing, syrup production, transport, refrigeration, etc.) of Soda XXX has greatest environmental impact?	***Industrial Example:*** Comparing the environmental impacts of paper vs. plastic grocery bags.
Agricultural Example: Which part of compost production contributes the most to the environmental impact?	***Agricultural Example:*** Comparing the environmental impacts of using compost vs. fertilizer.
2) Where are the boundaries that define the beginning and the end of the systems?	
Attributional LCA (the most common type of LCA)	**Consequential LCA**
This LCA method looks at the environmental impacts of a system in its current state.	This LCA method estimates how pollution and resources may shift within a system in response to hypothetical changes. Because these changes are not yet enacted, the consequential LCA is based heavily on educated assumptions.
Industrial Example: Based on current California transportation systems, is the environmental impact greater for commuting from point A to point B by bus or train?	***Industrial Example:*** If California High Speed Rail is built, what will be the environmental impact of commuting from point A to point B by rail vs. bus?
Agricultural Example: Based on current production processes, what are the environmental impacts of beef production?	***Agricultural Example:*** How would the environmental impacts of beef production change if the co-product from corn ethanol production (dried distillers grain with solubles) is used for feed? How would that change affect the total land requirements?
3) Is the objective to evaluate the current system or to predict the impacts of alternative production methods?	
Cradle-to-Grave (Useful for consumers and the industries)	**Cradle-to-Gate** (Useful for companies with no control over a product once it leaves their facility)
This LCA method considers the entire life cycle of the system, including raw material extraction, production, use, and final disposal.	This LCA method considers a product's life cycle up to the point that the product leaves the manufacturer's or producer's "gate."
Industrial Example: Cell phone — life cycle begins with extraction of raw materials used to produce the phone and battery, and includes consumer use (charging phone). End boundary is when the cell phone is thrown away and ends up in a landfill or other disposal site.	***Industrial Example:*** Cell phone — the life-cycle end boundary occurs at the cell-phone manufacturing plant gate.
Agricultural Example: Wine follows the life cycle from mineral mining and fertilizer production through field cultivation, wine-making and bottling, consumer use of wine, and final recycling or disposal of glass bottle.	***Agricultural Example:*** Wine grapes — the life-cycle end boundary occurs when harvested grapes leave the farm gate for delivery to the winery. This is useful for growers to identify the environmental impacts of their system.

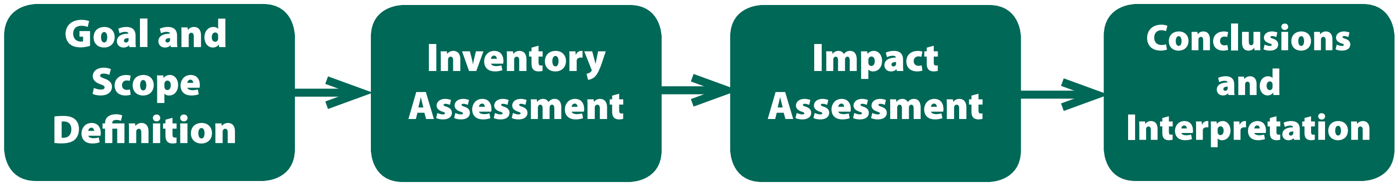


Figure 2. Life-Cycle Assessment Components. The four main components of LCA are often interdependent, as the results of one component will inform how other components are completed.

This type of combined analysis is especially useful for comparing alternatives that serve the same purpose but differ in the initial and/or operating costs. A life-cycle cost analysis can also be useful during the design phase of a system in order to estimate the costs of compared alternatives and to select the design with the lowest overall costs. Combining LCA (excluding labor) with a life-cycle cost analysis gives businesses the ability to validate or compare the financial benefits of alternatives that may reduce environmental impacts.

LCA Components

The main components of any LCA are: 1) Goal and Scope Definition; 2) Life-Cycle Inventory; 3) Impact Assessment; and 4) Conclusions and Interpretation. During the Goal and Scope Definition stage, the system boundaries are set and a process-flow diagram is constructed to identify material and energy inputs and outputs for the system. The inputs and outputs are quantified during the Life-Cycle Inventory phase. The environmental impacts of these outputs are estimated during the Impact Assessment phase, after which Interpretation of the results can occur. These four components are defined below.

Goal and Scope Definition

The Goal defines the purpose and method of life-cycle assessment that will be used in a given study, including its audience, application, and objectives. The Scope defines the function of the product, the functional unit (see opposite), the system boundaries, and any data requirements, assumptions, or limitations.

The system boundaries identify which life-cycle stages and parts of associated systems are included in the LCA. See Cradle-to-Grave vs. Cradle-to-Gate in Table 1 for an example of system boundaries. Geographic, time-related, or environmental boundaries may also be included. Environmental impacts associated with workers and their labor are often excluded, such as the impacts associated with the transport of workers from their homes to the workplace.

System boundaries greatly influence the findings of an LCA. For example, many refrigerated products have high energy use associated with the consumer-use phase (home refrigeration). Exclusion of the use phase in an LCA of a refrigerated product, therefore, may lead the LCA practitioner to miss an important component of the overall environmental impact. On the other hand, the LCA practitioner may have little interest in the use phase of the refrigerated product if the audience of the study is not consumers or consumer interest groups.

Inventory Assessment

The inventory assessment of an LCA is essentially the data-collection phase. Typical system inputs are energy and material use, and typical outputs are products, co-products (defined below), waste, and emissions to the air, water, and soil. All the necessary inputs and outputs across the product life cycle are gathered and quantified.

Public and private databases are used extensively in the inventory phase of most LCAs. Existing life-cycle inventory datasets from many previously studied systems are available (see Appendix B) and are often utilized by LCA practitioners as a data source for subsystems found within the larger system studied. For example, the life cycles of energy production methods (fuel, electricity, etc.) have

Functional Unit: Definitions and Nuances

The functional unit in Life-Cycle Assessment allows for comparison of alternative products and services (Guinée et al., 2002). The functional unit is a measure of the service provided by the product. For example, the functional unit for an LCA comparing compact fluorescent to incandescent light bulbs might be 1,000 hours of light, at 800 lumens. In agriculture, functional units are often expressed as weight or volume of the crop or on a per-area basis (see descriptions below).

In LCA, environmental impacts and resource consumption are conveyed relative to the selected functional unit, thus providing a reference for comparison. For example, a grower might be interested in energy use per acre or per ton of product. The choice of functional unit significantly influences the findings of an LCA, especially in the multifunctional systems found in agriculture. Functional units used in agricultural LCAs can be classified according to three main categories: 1) quantity of the product, or crop yield; 2) land area; or 3) stored energy (e.g., calories in food). Each of these is described briefly below:

1) Quantity of the Product

Environmental impacts can be calculated based on a set amount of product produced, or impact per product quantity (e.g., per ton). Product quantity functional units identify the most efficient production methods in terms of lowest impact per product weight or volume.

2) Land Area

Environmental impacts can be calculated based on the amount of land area used in creating the product, or impact per land area (i.e., per acre). Employment of both mass and land area functional units is typical in agricultural LCAs. Land area is rarely used independently.

3) Stored Energy

Environmental impacts can be calculated based on the amount of chemical energy bound in the final product, or based on the impact per unit energy associated with final product. In an agricultural LCA, these are the calories stored in the harvested crop. This functional unit is less common in agricultural LCAs due to the complex functions of food to deliver nutrients as well as energy. However, stored energy has been used as a functional unit to evaluate corn ethanol production systems, where stored energy is the product of interest.

— Cerutti et al., 2011

been studied extensively and these datasets can be used in other LCAs where energy use is required.

Many systems studied in LCA produce multiple products, known as co-products. For example, the logging industry's main product may be board wood but co-products often include woodchips or sawdust. In LCA, environmental impacts should be allocated to the main product and co-products. Allocation of environmental impacts occurs in various ways and is often based on the mass or volume of the co-product. For example, environmental impacts related to the transportation of goods can be distributed across all products transported in one truck or train based on a product's mass.

Impact Assessment

The impact assessment phase of an LCA translates the inventory data into meaningful values, called environmental indicators, which inform us about the environmental impacts of a product or system. LCA practitioners choose appropriate indicators for their particular study. Indicators are unlike inventory data that measure weights of materials or emissions and joules of energy. Instead, indicators simplify large datasets by categorizing and scoring inventory data using a sort of point system for easy comparison.

Global warming is one common environmental impact and the corresponding environmental indicator is global warming potential (GWP). GWP translates nitrous oxide (N_2O), carbon dioxide (CO_2), and methane (CH_4) emissions data gathered during inventory assessment into to their CO_2-equivalents, and calculates the potential of the total greenhouse gas (GHG) emissions to change the earth's average temperature (by trapping radiation in the atmosphere) over a specific time span, commonly 100 years. The GWP over 100 years for carbon dioxide is 1. For methane, the GWP is 25 and for nitrous oxide it is 298. In other words, the GWP of nitrous oxide is 298 times more powerful than carbon dioxide. Impact assessment can further transform GWP into scores relating to the broader impacts of global warming, including loss of biodiversity, loss of crops, and damage to humans. Broader impact scores are more comprehensible and often more relevant for decision makers.

Water quality is another environmental impact category, expressed as a metric to assess an aquatic ecosystem's ability to support organisms as well as human needs. Indicators of water quality include nutrient levels like phosphorus and nitrogen. Other environmental impact categories can estimate how many people will be made ill or die due to the production of a product, or give similar equivalents for destruction of habitat, etc. Table 2 gives more examples of environmental impact categories and examples of measurable environmental indicators (also know"inventory data").

Conclusions and Interpretation

The conclusions and interpretation phase identifies "hotspots" in the life cycle of a given product or comparison of several alternative products. Hotspots indicate where the use of alternative practices or goods will minimize the overall environmental impacts of the product in question. When LCAs are made available to the public, they can be useful for groups such as farmers, policy makers, and consumers only if details about how the LCA was done are reported with the results. Users such as farmers can evaluate their own production systems for hotspots identified in an LCA. See Appendix C for suggestions on interpreting a completed LCA to apply the findings to one's own system.

Life-Cycle Assessment in Agriculture

The environmental impacts and hotspots of an agricultural production system can differ depending on many factors. First, a wide range of management practices exist, and selection can vary depending on the cropping system (for example, perennial or annual), grower preferences and market trends (for example, organic or conventional). Second, a system depends on site-specific factors including climate, water availability, soil type, topography, cultivar selection, operation size, and land use history.

For example, perennial cropping systems differ from annual systems in many ways. Perennial crops (e.g., fruit and nut crops) remain in place for successive years and frequently utilize permanent cover crops, no-till systems, and drip irrigation. In annual cropping systems, the whole system tends to be tilled, re-planted, and fertilized every year. For example, the National Agricultural Statistics Services reported average nitrogen application (pounds per acre) to be 140 for corn (2010), 142 for tomatoes (2010), and 23 for wine grapes (2009).

The agricultural flow diagram on page 11 shows how the production system of an agricultural product and the environmental system may interact (Figure 3).

Agricultural Case Study: Conventional vs. Organic Milk

When conducting an LCA, environmental impacts that have strong effects on the production system or on the environment are known as hotspots. This study of milk production identifies hotspots in the production system (Cederberg and Mattsson, 2000).

Table 2. Environmental Impacts and Examples of Environmental Indicators (Associated Inventory Data)

Environmental impacts are defined as the consequences of pollution or resource use. Environmental Indicators (often called "potentials") are used with life cycle inventory data to quantify environmental impacts. In any given life-cycle assessment, the Goal and Scope determine the specific suite of environmental impacts and indicators that will be used. This table lists some common environmental impacts and the associated environmental indicators that are used in agricultural LCAs. This list is not a complete inventory of such associations.

Environmental Impacts	Examples of Environmental Indicators (Associated Inventory Data)
Natural Resources	
Abiotic resource depletion	Crude oil, mineral fertilizer (NPK), water
Biotic resource depletion	Wood for construction
Ecological Impacts	
Global warming	CO_2, CH_4 and N_2O emissions from fuel combustion
Depletion of stratospheric ozone	Methyl bromide used as a soil fumigant
Acidification	Sulfur dioxide emissions from a coal power plant
Eutrophication	Discharge of detergents containing phosphates
Habitat alterations and biodiversity impacts	Land use change
Human Health Impacts	
Toxicological impacts	Heavy metal accumulation

— Modified from Baumann and Tillman, 2004; and Haas et al., 2000.

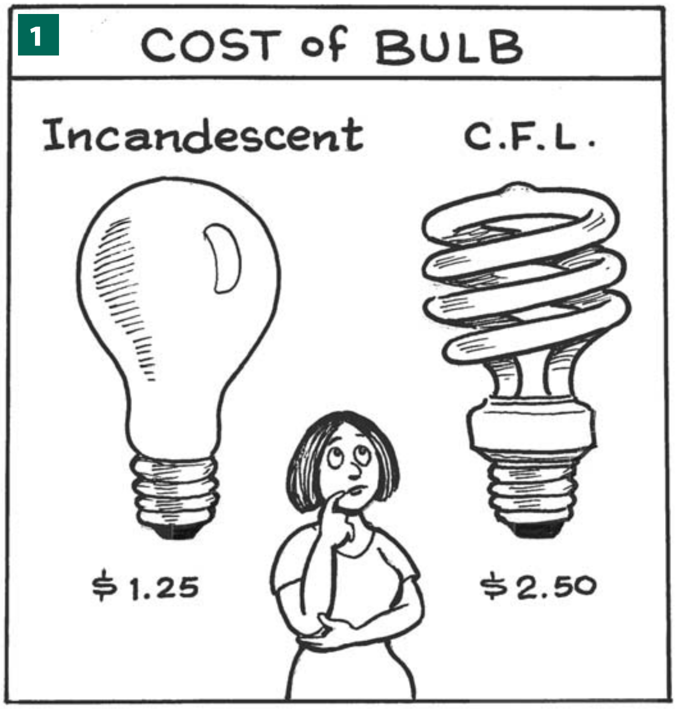
Goal and Scope Definition

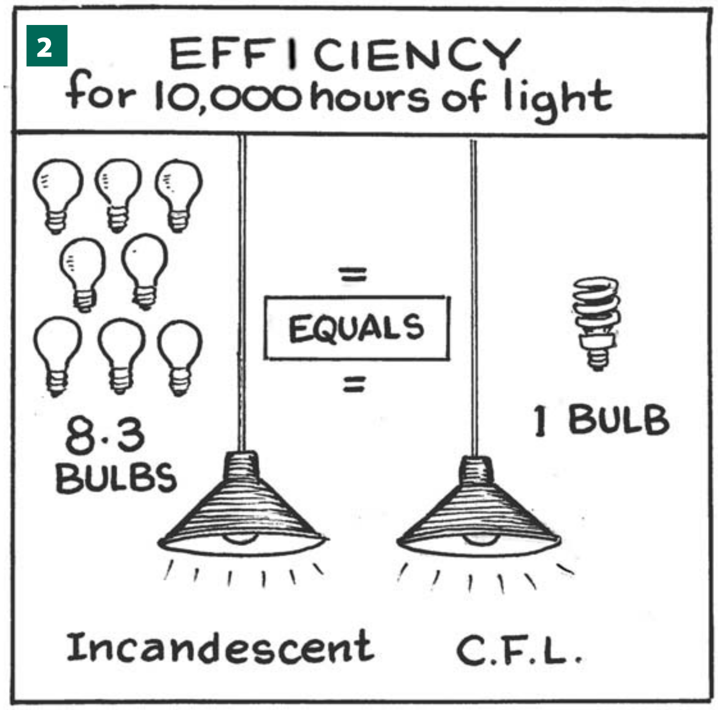
Goal and Scope of Life-Cycle Assessment for Conventional vs. Organic Milk Production. The study's goal was to determine if milk production systems with high input of resources ("conventional") have a greater environmental impact than systems with low inputs ("organic") achieved by using local fodder and plant nutrients.

Functional Unit and Time Frame. The functional unit was a measure of the energy in the milk leaving the farm gate. The exact functional unit was 1,000 kg of milk (corrected to account for the fat and protein content of the milk). The time frame was one year.

System Boundaries. The system begins with the production of farm inputs like pesticides, fertilizer, and seed necessary to produce the food for the dairy cows. The system includes the dairy cows housed in dairy farms with organic or conventional practices. It ends after transport of the milk off the farm. Only the organic farm included the production of pea fodder, while only the conventional farm included fertilizer and pesticides in the production of grain fodder.

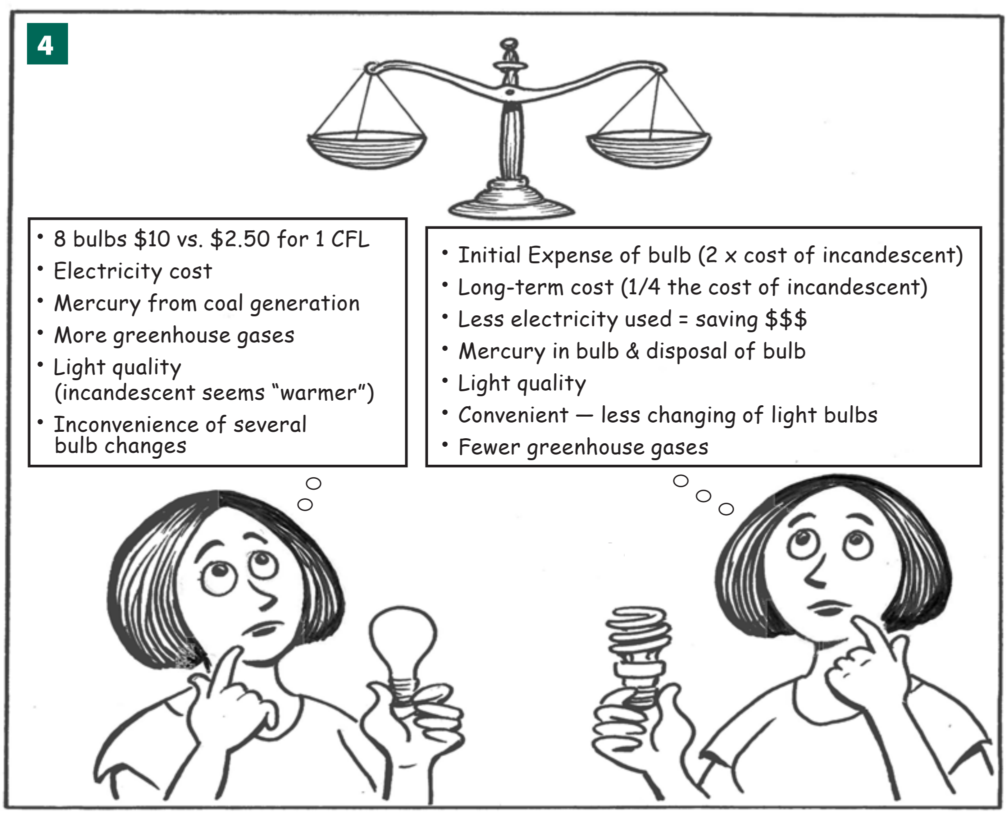
Buildings and machinery were excluded because they were similar in both conventional and organic farming systems. Allocation of environmental impacts among co-products was also necessary. For example, both systems produced meat and milk. The distribution of the energy and protein needed for a dairy cow to produce the milk, maintain herself, and support her pregnancy





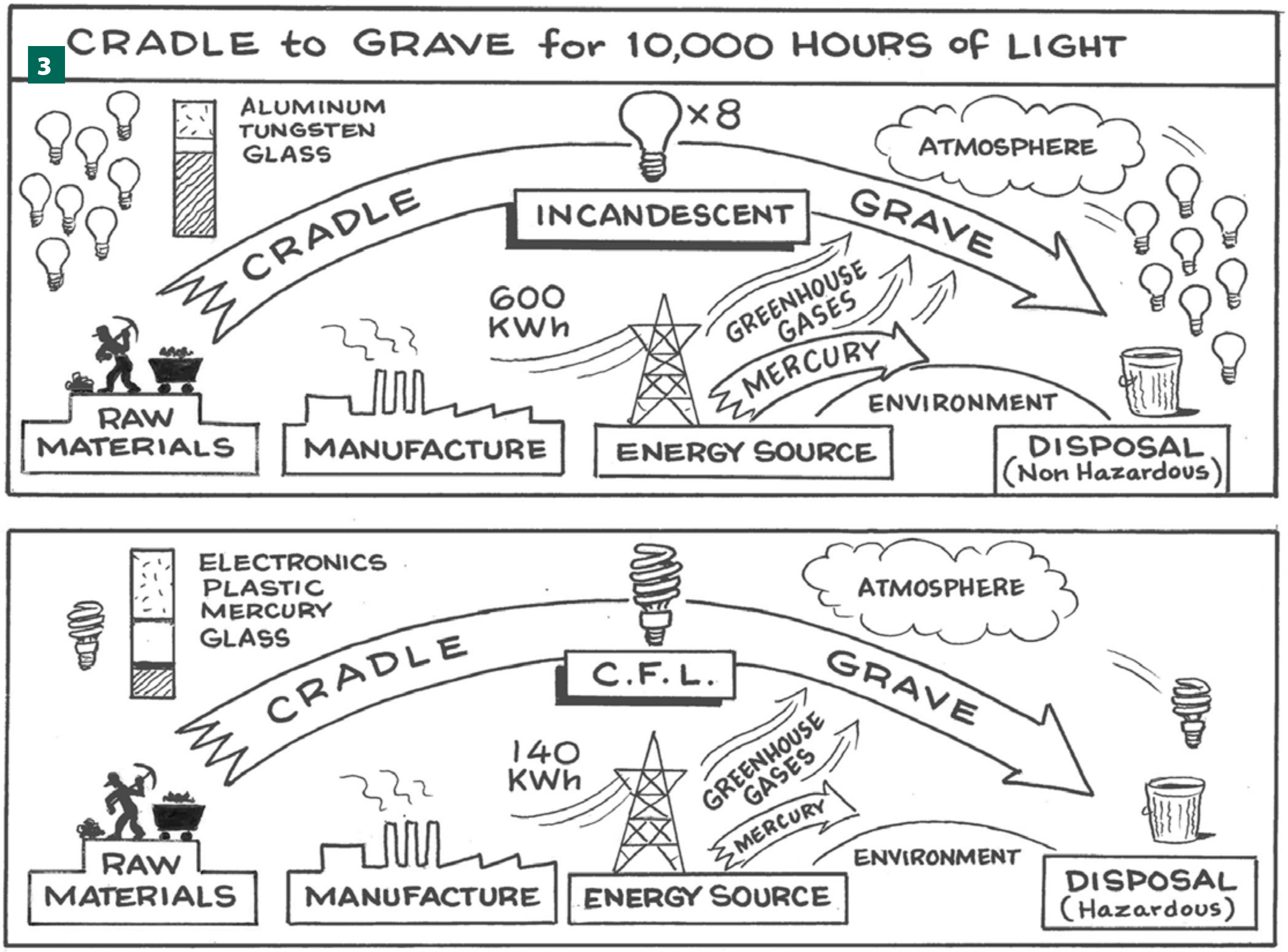
LCA-type calculations are used in daily life by consumers, but these calculations are not as detailed as one would find in a real LCA. For example, if you're shopping for a light bulb, there are many choices available. But in the price range of most consumers, the choice boils down to either using a compact fluorescent bulb (CFL) or an incandescent bulb. If you are simply looking at price, the choice is simple: the incandescent...

...However, more information about the cost over the "life span" of the bulbs shows the situation in a very different light. It would take more than eight incandescent bulbs to equal the typical compact fluorescent bulb (CFL) lifetime of 10,000 hours. So because it lasts so long, the CFL is far from being twice as expensive as an incandescent bulb. The CFL is actually roughly one-quarter the cost of an incandescent bulb.



Consumers, and society in general, are becoming more aware of the environmental impacts of our manufacturing and agriculture.

Life-Cycle Assessment is a tool that can be used to identify and quantify environmental impacts so that they may be more efficiently addressed.



…An even closer look at the manufacture of incandescent and compact fluorescent (CFL) light bulbs and the energy use required of the bulbs and their disposal, reveals that CFLs — although more efficient energy-wise — are considered hazardous waste due to the small amount of mercury they contain.

However, due to the greater energy use accruing to incandescent bulb use if the energy supply comes from coal, there is actually more mercury emitted into the environment from the use of the less-efficient incandescent bulbs, compared to the mercury contained in the CFL. Until very recently, 50% of energy in the U.S. has been from coal, although this has presently dipped to 34% due to low natural gas prices.

Compared to the CFL, the incandescent bulb's energy use emits additional greenhouse gases.

Sustainability encompasses the concept of stewardship—the responsible management of resource use—and can be defined as having three dimensions, also known as the "Three E's" of sustainability: Economics, Social Equity, and the Environment (UN General Assembly, 2005). The vitality of both the economy and society depend on maintaining a healthy environment, which is often the focal point for improving sustainability.

led to allocation of environmental impacts across these two products (85% to milk, 15% to meat). Manure production was not treated as an output product because it stayed "on-farm" and was used for fertilizer on both the organic and conventional farms. So no allocation was necessary for manure.

Inventory Assessment

Data were collected from two relatively large dairy farms in western Sweden that follow a current commercial production scheme.

Impact Assessment

Environmental Impacts and Indicators Used in LCA for Conventional vs. Organic Milk Production. In order to address the Goal and Scope, several environmental indicators were selected to evaluate the conventional and organic milk production systems: resource consumption (energy, material and land use), human health (toxicity via pesticide use), and ecological consequences (global warming, acidification, eutrophication, photo-oxidant formation, and depletion of stratospheric ozone).

Conclusions and Interpretation

Interpretation and Hotspots. Of the environmental impacts selected above, several were identified as hotspots.

Resource Use in Conventional vs. Organic Milk Production. Energy use was a hotspot identified in this LCA. Primary energy sources included coal, crude oil, natural gas, natural uranium, and hydropower, and were expressed as MegaJoules (MJ) per functional unit. The use of primary energy was 3,550 MJ per functional unit (1,000 kg of milk) in the conventional system and 2,511 MJ per functional unit in the organic system. The greater use of concentrated feed and synthetic fertilizers in conventional milk production contributed to greater energy use in conventional systems.

It is also possible to look at the different kinds of energy that compose the total energy used by the two farming systems. For example, coal use was nearly four times greater (4.87 vs. 1.23 MJ per functional unit) in conventional than organic milk production due mainly to refining components (mainly drying beet fibers) in the feed concentrate, which was fed to cows in conventional milk production. In contrast, electrical energy consumption was greater per functional unit in organic than conventional milk production. Identifying the relative contributions of these energy sources to the other environmental impacts can help farmers evaluate which practices and goods to use in their production system.

Nutrient use represented another hotspot. Phosphorus is a limited global resource, and its conservation and judicious application is becoming paramount in agriculture. In both milk production systems, phosphorus was applied almost exclusively as fertilizer for fodder. The amount of phosphorus used per functional unit was nearly three times greater in the conventional than in the organic milk production system. This was attributed to the applied fertilizer in feed imported to the farm.

Soil phosphorus levels in the conventional system were also greater than in the organic system. This suggests that phosphorus use was less efficient in the conventional system, and that accumulation and subsequent leaching of plant-available phosphorus from soil could occur, contributing to downstream eutrophication in streams, lakes, and oceans. (See Ecological Consequences, on page 12.)

Human Health in Conventional vs. Organic Milk Production. Pesticide application was identified as a hotspot contributing to long-term toxicity of the environment and production system. The conventional system used the pesticides monocrotofos and endosulfan for insect control during soybean production. The conventional system applied 118 g of pesticides per functional unit, whereas the organic system used just 11 g of pesticides per functional unit. Nearly 75% of the pesticides in the conventional system came from its high use of soybean meal. The authors of this study suggest that the conventional system should incorporate

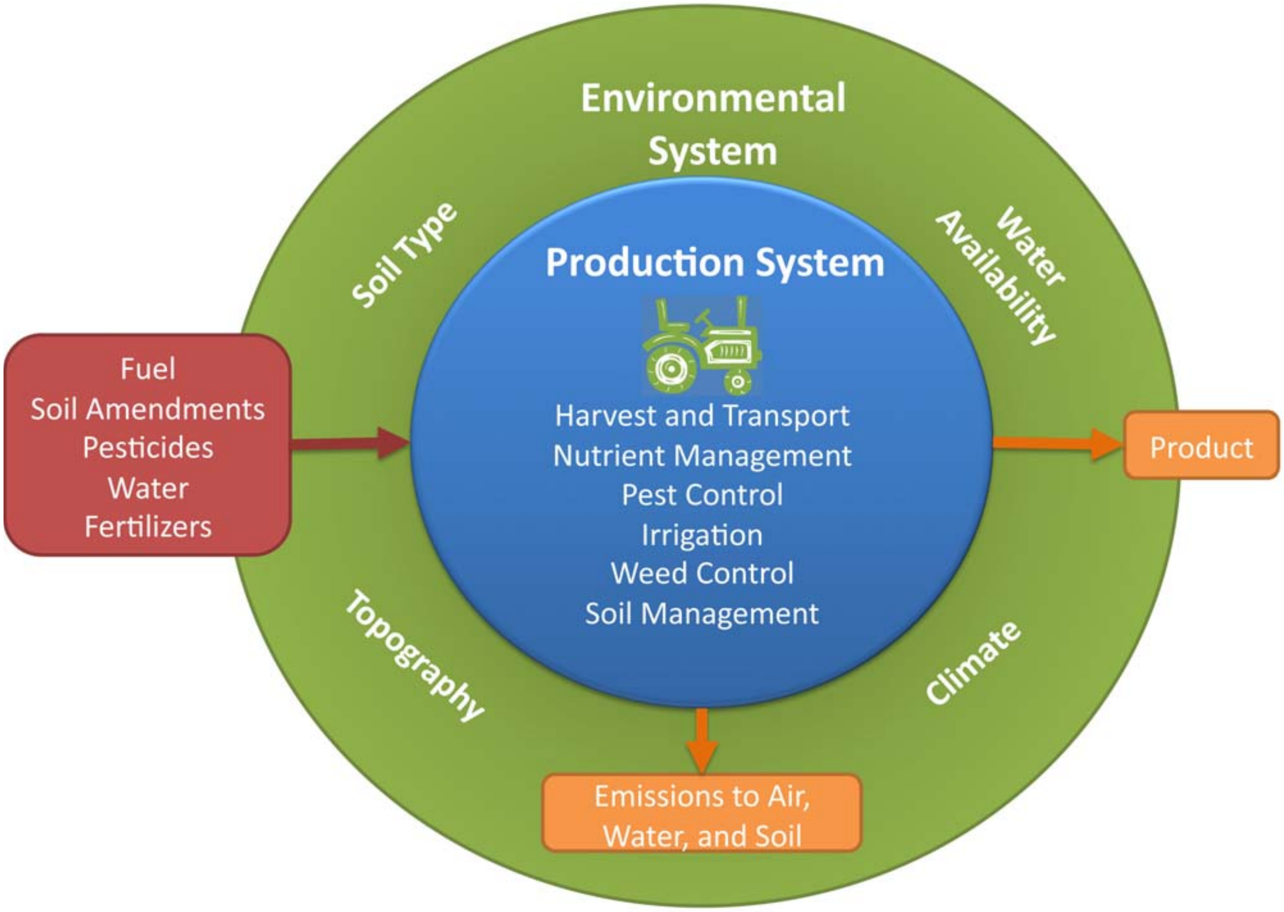


Figure 3. On-Farm Life-Cycle Components and Flow Between the Environment and the Production System

This simplified process flow diagram shows the main components of the on-farm phase of an agricultural product's life cycle. In the diagram above, view the farm "production system" as a manufacturing plant.

At the end of the on-farm life-cycle phase, the product is ready to be transported to the next phase of the life cycle (for example, to a processing plant or packaging facility).

Material inputs (such as fuel and fertilizers) and management practices used in the production system (such as nutrient and soil management) result in the release of emissions into the environmental system (for example, nitrogen loss through nitrate leaching and greenhouse gas emissions).

The production phase of an agricultural life-cycle assessment (LCA) is unique because the production system is open to the environment.

In a non-agricultural LCA, environmental impacts associated with the production system generally have little effect on the production system itself. In an agricultural LCA where the production system is open to the environment, many environmental impacts can affect future production (for example, biodiversity impacts).

In addition, site-specific biological factors like soil type, water availability, topography, and climate affect how growers manage their production system (for example, soil mineralogy can affect nutrient input requirements).

By disking only alternate alleys, wine-grape growers can protect the soil resource and enhance their access to the vineyard. Photo: Rex Dufour, NCAT

an integrative farming systems approach to reduce pesticide use.

Ecological Consequences. The global warming potential in the LCA of milk production was affected by emissions of the greenhouse gases methane, nitrous oxide, and carbon dioxide. Nitrous oxide emissions were mainly derived from fertilizer production, and carbon dioxide was generated from fuel use. However, methane was the most important contributor to global warming potential in milk production. The feeding strategy of using more roughage and fodder in organic systems led to 10 to 15% greater methane emissions from cows in the organic than conventional system. Another ecological consequence identified in milk production was eutrophication in natural water systems, as mentioned above.

Comments on Interpretation of Hotspots. This study demonstrates how the context in which an LCA is conducted can affect the outcome in response to the identified hotspots. The indirect effect of land use on aesthetic and cultural value is difficult to quantify, but nonetheless must be considered when proposing methods to reduce the impacts of these hotspots. While the use of greater amounts of land for organic dairy production could be viewed negatively, in this case, it is a land use that is highly valued in Sweden for its attributes related to human health. This is because in Sweden and other parts of Europe, society places strong value on the preservation of open, bucolic landscapes and cultural traditions. So organic dairies with greater pasture acreage compared to conventional dairies are viewed more positively.

Sample Agricultural Life-Cycle Assessments in California and the U.S.

A number of LCAs that look at agricultural systems in California are currently underway. A few are presented here to demonstrate some of the various ways of implementing LCA. The first two, wine grapes and wine, show how LCA can differ in terms of goals, spatial scales, and system boundaries. An almond LCA is described to demonstrate ways to use multiple functional units. Following these examples is a list of published agricultural LCA studies that demonstrate cropping systems in other areas of the U.S. and the world. These studies are also listed in Appendix B.

Wine Grape and Wine Production LCAs

Two collaborative projects evaluating the life cycles of wine grape and wine production in the state of California are currently underway with the Wine Institute and with the USDA-Agricultural Research Service and the University of California, Davis. These complementary projects aim to help growers, grower groups, wine producers, and policy makers communicate and make decisions about reducing the environmental impacts associated with wine grape and wine production. Although both studies focus on the wine grape industry, they occur on different spatial scales, and possess different boundaries, goals, and scopes. Both projects are funded by California Department of Food and Agriculture (CDFA) Specialty Crop Block Grants.

The USDA-ARS/UC Davis project focuses on wine grape production from cradle-to-farm-gate in Lodi and Napa, two important yet very different wine-growing regions. Vineyard management differs across regions and within each region due to variations in climate, water availability, soil type, topography, cultivar selection, operation size, and land-use history. Through this LCA, researchers compare the range of management regimes found in each region and identify the production practices with the lowest environmental impacts.

In order to better understand differences between the two regions, environmental impacts will be expressed relative to two functional units: 1) Land Area—total yield from one acre (e.g., global warming potential per acre); and 2) Mass of Product—one ton of grapes (e.g., global warming potential per ton of grapes). For more information on functional units, see page 5. This will allow quantification and comparison of the impacts based on land area as well as product volume. This LCA's main source of data is from face-to-face interviews and vineyard-management records collected across 90+ vineyard sites from 30 vineyard managers in the two regions. Results from this project will be incorporated into the wine-grape production life-cycle phase of the Wine Institute's LCA.

The Wine Institute project has broader boundaries and looks at the life cycle of all California wines from cradle-to-grave. This project aims to identify the relative contributions of various phases of the life cycle (i.e., wine-grape cultivation, wine production, bottling, etc.) to the industry's overall environmental impacts and to integrate identified hotspots into existing tools to drive statewide industry improvements.

Both projects incorporate on-farm biological processes related to emissions of greenhouse gases from soils —i.e., carbon dioxide (CO_2), nitrous oxide (N_2O), and methane (CH_4)—into their LCAs via a denitrification-decomposition model developed by Applied GeoSolutions (see Appendix A). The goal is to capture the environmental impacts from soil processes like nitrogen and carbon cycling, which vary across landscapes and land-management practices.

Wine-grape growers have demonstrated that alley cropping can mitigate some environmental impacts of vineyards, as well as being pleasing to the eye. Photo: Rex Dufour, NCAT

Ultimately, the results of these two LCAs will inform growers and wine producers about the environmental impacts of the various phases of the grape-to-wine life cycle, as well as specific practices that may reduce the impacts of the wine-grape production phase. Both projects will help develop useful metrics to identify achievable targets for reducing environmental impacts.

Almond Production LCA

An LCA of California almond production began in 2010, focusing on estimating life-cycle energy and greenhouse gas (GHG) emissions for "typical" conventional production across the state. The system boundary is cradle-to-processor gate over 25 years (productive lifespan of a typical almond orchard) and includes almond-production operations from tree nursery through hulling and shelling operations. While the modeling examines almond production based on area (one acre of orchard), two functional units are considered: 1 kg of almond kernels, and 1 nutritional calorie. (See page 5 for information about functional unit selection.) For a description of the research and results for

This organic almond grower planted bell beans in the orchard alleys to protect the soil and provide low-cost nitrogen that has a low environmental impact. Photo: Rex Dufour, NCAT

the first stage of research, see Kendall, et al., 2011, listed in References.

The impact-assessment categories considered include primary energy consumption, global warming potential, and a number of other air-pollution categories such as smog formation potential, acidification, and eutrophication potential. (See Glossary for more definitions of these impact categories and environmental indicators.)

Hotspots for energy and emissions include energy demand for irrigation water (calculated on a regional basis for the California Aqueduct, gravity-fed surface water, and pumped groundwater), and nitrogen fertilizer, which is energy-intensive to produce and results in nitrous oxide (N_2O) emissions from soils. N_2O is a potent greenhouse gas, with a 100-year global warming potential of 298. However, almond orchards produce a significant quantity of residual biomass, including wood removed from the orchard, hulls, and shells. Use of this biomass—particularly trees removed at the end of the orchard's productive lifespan and shells removed during processing—to generate electricity can offset a large proportion of the total system greenhouse gas emissions by displacing fossil fuels used for electricity generation in California.

This study shows the importance of examining the full life-cycle and systemwide implications of agricultural systems. This research is slated to be complete in the summer of 2013 and is funded by the Almond Board of California (project number 10-AIR8-Kendall).

Several Additional Examples of LCAs for Other Commodities

Numerous studies have looked at the environmental impacts of agriculture. For example, studies using LCAs have evaluated the energy consumption associated with various practices in apple-production systems in New Zealand; the global impacts of food production (e.g., Pfister et al., 2011; Gonzalez et al 2011); and the environmental impacts of biofuel production with corn in the Midwest (e.g., Powers, 2007; Feng et al., 2010; Wang et al., 2011), or with rice husks in Thailand (Prasara-A and Grant, 2011). This small yet diverse array of examples of LCA demonstrates the technique's wide applicability. See Appendix B for full citations of these studies.

Relevance of Life-Cycle Assessment in National and Regional Policy Programs

Agriculture in California and other regions of the United States can benefit from the use of LCA. In the context of sustainability—the "Three E's" of economics, social equity, and the environment (United Nations General Assembly, 2005)—LCA can be used to develop and support agricultural certification programs and policies in the state of California. A few examples of national programs that utilize LCA are also described.

LCA and Certification Programs. Numerous measures of sustainability for agricultural systems have been developed and implemented by researchers and practitioners in the agricultural sector. This has been driven partly by consumer demand for "environmentally friendly" products and partly by stricter environmental regulations. Ideally, these measures of sustainability used by programs such as the Climate Action Reserve, the Stewardship Index, and California's incipient Cap and Trade System (see Further Resources for more information on these programs) enable producers to benchmark, compare, and communicate sustainability performances such as carbon neutrality. These emerging opportunities are designed to provide incentives including new markets and marketing strategies, and improved long-term profitability.

Incentive-based agricultural policies and certification programs frequently require adherence to a standard set of practices to qualify. Becoming certified under some programs may also lead to improved marketability, as has been demonstrated in the wine-grape industry by the USDA National Organic Program, the Fish Friendly Farming label of the California Land Stewardship Institute, and the Lodi Rules accredited by Protected Harvest. The Stewardship Index for Specialty Crops takes another approach, in which desired environmental and agricultural outcomes are defined, but the practices to achieve such outcomes are not prescribed. See Further Resources for additional information on these programs.

In order for more areas of the agricultural industry to be considered for programs like these, scientists must develop reliable methods to quantify, model, and set achievable targets for reducing environmental impacts specific to agricultural sectors, cropping systems, and/or regions. These methods must be practical enough to be implemented on-farm without large investment of money or time by the farmer.

Although some agricultural research methods and certification programs take a "systems approach" to understand how all parts interact within a whole farming system, many do not consider entire life cycles of a production system. A narrow approach, which analyzes only a component of a production system, may mistakenly lead to the shift of environmental impacts from one to another area of the production chain, instead of an absolute reduction of the impacts.

An increasing number of almond growers are encouraging winter alley crops in order to reduce runoff and improve soil quality. Photo: Rex Dufour, NCAT

LCA has the advantage of following all products and processes necessary for producing the crop ("cradle-to-farm gate"), delivering it to the consumer ("cradle-to-consumer"), and/or its final disposal ("cradle-to-grave"). It allows for evaluation of nearly all environmental impacts of the farming system and contributing systems, and identifying where in the process these environmental impacts occur. Farmers and farmer groups can utilize LCA's "whole systems" approach in order to identify their greatest opportunities for reducing environmental impacts.

Similarly, LCAs provide information to policy makers about which agricultural practices and components are most effective in reducing environmental impacts such as energy use and carbon emissions. This information can then guide funding to programs that incentivize and/or disincentivize particular practices in agricultural systems. It can also provide insight for prioritizing government- or farmer group-sponsored farmer-training programs focused on improving overall agricultural sustainability.

LCAs, Carbon Markets, California, and Assembly Bill 32

The agricultural sector can use LCAs to improve sustainability (see Figure 2) and respond to the tighter restrictions on resource use and greenhouse gas emissions. Agriculture and forestry in California are accountable for roughly 8% of the state's total greenhouse gas emissions (GHGs) (Carlisle et al., 2010). Although the state has not mandated emissions caps for the majority of the agricultural sector, California is proceeding in implementing its Global Warming Solutions Act, Assembly Bill 32, which requires the state to reduce its greenhouse gas emissions to 1990 levels by 2020. AB 32 will directly and indirectly affect the agricultural industry through increased costs for carbon-based fuel, energy, and fertilizer, and tighter restrictions on new development. AB 32 may also funnel research dollars to better understand agriculture's role as a source and a sink for carbon.

Through implementation of AB 32, new funds will become available to support reductions in GHG emissions and help California adapt to climate change. As this publication goes to print, the California legislature is about to begin appropriating funds from carbon credit auctions. There is on-going discussion about whether funding from these auctions ought to support: 1) research on carbon sequestration in agricultural systems; and 2) incentives for farmers to reduce GHG emissions in agriculture. In addition, agricultural protocols (sets of practices and rules) are in development to guide eligibility in California's carbon market. Having LCAs available for particular crops or cropping systems will inform protocol development and the provision of public funding to the practices with the most significant climate benefits. Updates on these programs are found online at California Climate and Agriculture Network (www.calclimateag.org) or the California Air Resources Board (www.epa.gov/otaq/fuels/renewablefuels/index.htm).

LCA and National Programs

LCA is currently being used on a national level to reduce the environmental impacts of transportation fuels. The Renewable Fuel Standard is a policy set in place by the U.S. EPA to decrease the life-cycle-based emissions of the nation's transportation fuels that are bought and sold beginning in 2012. As a result of this policy, companies are required to produce fuels that, on a life-cycle basis, reduce the carbon intensity relative to current gasoline and diesel. This policy provides an example of how large economic sectors similar to transportation, such as agriculture, could be regulated in the future. It also directly affects current agricultural practices in the U.S. because it mandates annual requirements for biofuel production. More information can be found online at the U.S. EPA website at www.epa.gov/otaq/fuels/renewablefuels/index.htm.

Conclusions

LCAs can be useful tools for farmers, farmer groups, and policy makers. For example, LCAs can improve farmers' abilities to make decisions about their system's energy use. By pinpointing practices that have high or low environmental impacts, the farmer, or more likely the farmer group, can adjust and modify these practices to reduce environmental impacts (see Table 2). Ultimately, LCA can support green marketing strategies and will make it possible for grower groups to highlight opportunities for improved practices using self-audit tools.

Because developing an LCA requires extensive knowledge about working with large data sets and can be expensive to conduct, the purpose of this paper is not to teach farmers how to conduct their own LCA. Instead, we hope to spread understanding of LCAs and how the results can be interpreted and applied to one's own farming system (see Appendix C: LCA Interpretation and Application). In most cases, LCA reveals the hotspots and associated trade-offs of choosing certain production methods over others. Only rarely can it point unambiguously at the "best" technological choice to reduce the overall impacts of a given production system (Ayers, 1995). Nonetheless, the LCA process helps us understand the environmental impacts associated with each alternative we examine, and where these impacts occur (locally, regionally, or globally). LCA can enable growers to select the best production practices, materials, equipment, and goods to reduce the overall environmental impacts of their farming systems.

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Further Resources

California Air Resources Board
www.arb.ca.gov
The California Air Resources Board (ARB) is a part of the California Environmental Protection Agency (EPA), an organization that reports directly to the Governor's Office. The board's mission is to promote and protect public health, welfare, and ecological resources through the effective and efficient reduction of air pollutants, while recognizing and considering the effects on the economy of the state. The board's goals are to provide safe, clean air to all Californians, protect the public from exposure to toxic air contaminants, reduce California's emission of greenhouse gases, provide leadership in implementing and enforcing air pollution control rules and regulations, and provide innovative approaches for complying with air pollution rules and regulations.

California Cap and Trade Program
www.arb.ca.gov/cc/capandtrade/capandtrade.htm
The California Cap and Trade Program is a central element of California's Global Warming Solutions Act (AB 32) and covers major sources of GHG emissions in the state, such as refineries, power plants, industrial facilities, and transportation fuels. The regulation includes an enforceable GHG cap that will decline over time. The California Air Resources Board will distribute allowances, which are tradable permits, equal to the emission allowed under the cap.

California Climate and Agriculture Network (CalCAN)
www.calclimateag.org
California Climate and Agriculture Network (CalCAN) is a coalition that advances policies to support California agriculture in the face of climate change. CalCAN follows four guiding principles: 1) Employ a systems approach and full life-cycle analysis to evaluate potential climate-change solutions within agriculture, looking for co-benefits, true sustainability, and maximal impact; 2) Establish leadership within California's sustainable-agriculture sector on climate change policy based on best practices; 3) Seek common ground and develop collaborative partnerships among agricultural and environmental organizations; 4) Support policies that incentivize and direct revenue to fund research and sustainable farming practices that mitigate climate change and promote agriculture's sustainable adaptation.

California Department of Food and Agriculture (CDFA) Specialty Crop Block Grants (SCBGP)
www.cdfa.ca.gov/Specialty_Crop_Competitiveness_Grants
The California Department of Food and Agriculture (CDFA) Specialty Crop Block Grant Program (SCBGP) funds projects that solely enhance the competitiveness of California specialty crops. Specialty crops are defined as fruits, vegetables, tree nuts, dried fruits, horticulture, and nursery crops (including floriculture).

Climate Action Reserve
www.climateactionreserve.org
The Climate Action Reserve is the premier carbon-offset registry for the North American carbon market. Its goal is to encourage action to reduce greenhouse gas (GHG) emissions by ensuring the environmental integrity and financial benefit of emissions reduction projects. The Reserve establishes high-quality standards for carbon offset projects, oversees independent third-party verification bodies, issues carbon credits generated from such projects, and tracks the transaction of credits over time in a transparent, publicly accessible system

Code of Sustainable Winegrowing Self-Assessment Workbook
www.sustainablewinegrowing.org/swpworkbook.php
The Code of Sustainable Winegrowing Practices Self-Assessment Workbook is the foundation of the Sustainable Winegrowing Program (SWP) and a tool for program participants to measure their level of sustainability and to learn about ways they can improve their practices. The workbook addresses ecological, economic and social equity criteria through an integrated set of 14 chapters and 227 criteria, which includes a built-in system with metrics to measure performance.

COMET-VR — A USDA Voluntary Reporting Carbon Management Tool
www.comet2.colostate.edu
COMET is a Web-based tool that provides estimates of carbon sequestration and net greenhouse gas emissions from soils and biomass for U.S. farms and ranches. The system links a large set of databases containing information on soils, climate, and management practices to dynamically run the Century ecosystem simulation model as well as empirical models for soil N_2O emissions and CO_2 from fuel usage for field operations.

The system uses farm-specific information to provide mean estimates and uncertainty for CO_2 emissions and sequestration from soils and woody biomass and soil N_2O emissions for annual crops, hay, pasture and range, perennial woody crops (orchards, vineyards), agroforestry practices, and fossil fuel usage.

Fish Friendly Farming
www.fishfriendlyfarming.org
The Fish Friendly Farming Environmental Certification Program is run by the California Land Stewardship Institute, a nonprofit organization located in Napa County. Fish Friendly Farming® provides an incentive-based method for creating and sustaining environmental quality and habitat on private land. Landowners and managers enroll in the program, learn environmentally beneficial management practices, and carry out ecological restoration projects. The focus is on the land manager as the central figure in achieving and sustaining environmental quality. This approach implements the principles of state and federal environmental regulations. Three resource agencies—the Regional Water Quality Control Board, the National Marine Fisheries Service, and the County Agricultural Commissioner—provide an objective third-party certification.

International Wine Industry Greenhouse Gas (GHG) Protocol and Accounting Tool
www.wineinstitute.org/ghgprotocol
The International Wine Industry Greenhouse Gas Accounting Protocol was developed through a partnership between the Wine Institute of California, New Zealand Winegrowers, South Africa's Integrated Production of Wine program, and the Winemakers' Federation of Australia. The protocol will soon be released for use by the global wine industry. With increased attention to climate change and GHG emissions and offsets, the goal of the project partners is to provide a free, wine-industry specific, GHG protocol and calculator that will measure the carbon footprints of winery and vineyard operations of all sizes.

Lodi Rules
www.lodiwine.com/certified-green/lodi-rules-for-sustainable-winegrowing
The Lodi Rules sustainable wine-grape farming standards were developed by a stakeholder committee of 10 Lodi California Wine Grape Commission growers, four Lodi Wine Grape Commission staff, two UC Farm Advisors, a Lodi winemaker, a wildlife biologist from the East Bay Municipal Utility District, pest control advisers, and a viticulture consultant. The group submitted the draft standards to Protected Harvest, who arranged for them to be peer-reviewed by three scientists and then reviewed by the Protected Harvest Board. Some revisions of the draft standards were suggested via the review process. These changes were made and Protected Harvest accredited the standards.

Performance Metrics Program
www.sustainablewinegrowing.org/metrics.php
The California Sustainable Winegrowing Alliance (CSWA) has integrated performance metrics into the Sustainable Winegrowing Program to further promote, measure, and communicate continuous improvement. The metrics project provides growers and vintners with tools to measure, manage, and track their use of natural resources in order to optimize operations, decrease costs, and increase sustainability. The project enhances the California wine community's global leadership position in sustainable agriculture and production by remaining on the leading edge of sustainability. It enables participating SWP winegrowers to confidentially benchmark their performance metrics to drive innovation and adoption of sustainable practices. The project expands the means for communicating continuous improvement in performance to stakeholders. The initial set of metrics include: water use (vineyards and wineries), energy use (vineyards and wineries), greenhouse gas emissions (vineyards and wineries), and nitrogen use (vineyards).

Renewable Fuel Standard
www.epa.gov/otaq/fuels/renewablefuels/index.htm
The U.S. Environmental Protection Agency (EPA) develops and implements regulations to ensure that transportation fuel sold in the United States contains a minimum volume of renewable fuel. The Renewable Fuel Standard (RFS) program was created under the Energy Policy Act (EPAct) of 2005, and established the first renewable fuel volume mandate in the United States. As required under EPAct, the original RFS program (RFS1) required 7.5 billion gallons of renewable fuel to be blended into gasoline by 2012.

Stewardship Index
www.stewardshipindex.org
The Stewardship Index for Specialty Crops is a multi-stakeholder initiative to develop a system for measuring sustainable performance throughout the specialty crop supply chain. The project seeks to offer a suite of outcome-based metrics to enable operators at any point along the supply chain to benchmark, compare, and communicate their own performance.

USDA National Organic Program (NOP)
www.ams.usda.gov/AMSv1.0/nop
The National Organic Program mission is to ensure the integrity of USDA organic products in the U.S. and throughout the world. The NOP is a regulatory program housed within the USDA Agricultural Marketing Service that is responsible for developing national standards for organically produced agricultural products.

Wine Institute
www.wineinstitute.org
The Wine Institute advocates public policy for the responsible production, promotion, and enjoyment of wine. The institute represents California wine at the state, federal, and international levels; educates public policy makers and the media on the cultural and economic value of wine; takes a leadership role in the business and political network for wine; and assists members with information and guidance on legal, policy, and compliance issues.

Glossary

Acidification: Accumulation and deposition of acids (which cause widespread ecological damage) formed in the atmosphere by a reaction of sulfur dioxide and nitrogen oxide gases with water molecules. Emissions of sulfur and nitrogen gases come primarily from human sources such as electricity generation (i.e., coal power plants), factories, and motor vehicles.

Allocation: If more than one product is produced, the environmental impacts must be distributed among these products. This allocation is often performed based on weight or cost of the products.

Attributional LCA: Looks at environmental impacts of a system in its current state.

Carbon Intensity: The relative amount of carbon emitted from a particular fuel type when generating a specified amount of energy. For example, the carbon intensity to generate one megajoule of energy from coal is higher than that from solar power.

Carbon Neutral: Carbon emissions released as carbon dioxide (associated with transportation, energy production, land conversion, and industrial processes) are balanced with an equivalent amount sequestered, offset, or bought as carbon credits.

Cd (Cadmium): See Toxic Metals.

Hg (Mercury): See Toxic Metals.

Toxic Metals: Metals that form poisonous soluble compounds and have no biological role (not essential minerals). Examples include cadmium (Cd) and mercury (Hg).

CH_4 (Methane): A greenhouse gas which remains in the atmosphere for nine to 15 years and is over 20 times more effective in trapping heat in the atmosphere than **CO_2**. Human sources of CH_4 include landfills, natural gas and petroleum systems, coal mining and certain industrial processes, and agricultural activities such as rice cultivation, agricultural waste burning, and livestock digestive fermentation and waste management.

CO_2 (Carbon Dioxide): A naturally present heat-trapping atmospheric gas that is a part of the Earth's carbon cycle. CO_2 is the primary greenhouse gas accumulating in the atmosphere because human activities have increased emissions (e.g., fuel combustion) and disrupted the natural processes that remove CO_2 from the atmosphere (e.g., removal of forests).

Comparative LCA: Determines the benefits and tradeoffs between two or more comparable products.

Consequential LCA: Estimates how pollution and resource flows may shift within a system in response to hypothetical changes.

Co-Products: Some production systems result in more than one product (e.g., dairy operations have co-products of both meat and milk). LCAs will typically allocate some of the environmental impacts to each of the co-products.

Cradle-to-Gate: Considers a life cycle to the point where the product leaves the manufacturer's or producer's "gate."

Cradle-to-Grave: Considers the entire life cycle of the system, including raw material extraction, production, use, transport, and final disposal.

Criteria Air Pollutants: Six pollutants regulated and monitored by the U.S. EPA because of their high level of negative impacts on human and environmental health and their high prevalence in the U.S. The six pollutants are ozone, carbon monoxide, nitrogen dioxide, particulate matter, sulfur dioxide, and lead.

Ecotoxicity: In LCA, ecotoxicity refers to the effects of hazardous chemicals on both aquatic and terrestrial species.

Environmental Impacts: Consequences of pollution or resource use. In LCA, specific categories of environmental impacts are used, such as global warming potential (GWP), loss of diversity, resource use. See

Table 2 for more examples. Environmental indicators are used to assess the magnitude of an environmental impact.

Environmental Indicator: Measures that quantify environmental impacts, e.g., CO_2 emissions.

Eutrophication Potential: The potential of nutrients (e.g., nitrates, phosphates) to cause over-fertilization of water and soil, which can result in increased growth of biomass and the depletion of oxygen in the water, reducing populations of specific fish and other animals.

Functional Unit: Quantifies the goods or services delivered by the product system, providing a reference to which the environmental impacts can be related. For example, an LCA of almond production may employ a functional unit of one ton of almonds to reflect impacts like global warming potential (global warming potential per ton of almonds).

Global Warming Potential (GWP): In LCA, GWP is an environmental-impact category that represents the potential of greenhouse gas emissions to change the earth's average temperature (GWP is calculated over a specific time span, commonly 25 or 100 years).

Goal and Scope: Goal defines the LCA purpose and method, including the audience, the application, and the objectives of the study. Scope defines the function of the product, the functional unit (see page 5), the system boundaries, and any data requirements, assumptions, or limitations. Time span is included and defined when applicable.

Hotspots: These are parts of the life cycle identified during impact assessment as significant contributors to the total environmental impact.

Impact Assessment: Phase of an LCA that translates the inventory assessment data into meaningful values—called "environmental impact categories" and "environmental indicators"—which inform us about the environmental impacts of a product or system.

Impact Category: A classification representing specific environmental impacts due to emissions or resource use (i.e., climate change, loss of diversity). See Table 2 for details and examples.

Inventory Assessment: The data-collection phase of an LCA when all necessary inputs (e.g., energy and material use) and outputs (e.g., products, co-products, waste, and emissions to the air, water, and soil) across the product life cycle are gathered and quantified. If necessary, allocation across co-products occurs during this phase.

LCA Process Flow Diagram: A graphical representation of the linkages within and between the life-cycle phases of a product.

Life Cycle Assessment (LCA) is defined by the International Organization for Standardization as a tool for the analysis of the potential environmental impacts of products at all stages in their life cycle.

Life-Cycle Cost Analysis: A tool for the accounting of all costs incurred during the lifetime of a product. Costs include those associated with purchases, production, operation and maintenance (including labor), and disposal.

N_2O (Nitrous Oxide): A greenhouse gas that remains in the atmosphere for approximately 120 years and is over 310 times more powerful than CO_2. N_2O is produced and released into the atmosphere naturally from a wide variety of biological sources in soil and water, and is broken down and removed naturally from the atmosphere by sunlight (photolysis). Human sources of N_2O include agricultural soil management and combustion of fossil fuel.

NH_3 (Ammonia): The principal form of toxic ammonia. The toxicity increases as pH and temperature decrease. Animals, especially fish, are affected by the presence of toxic ammonia. Agricultural sources of ammonia include fertilizers and livestock waste.

Nitrate: Due to its mobility in water, nitrate is the primary form of leached nitrogen. Agricultural sources of nitrate include manures, fertilizers, and decaying plants and organic materials. High levels of nitrate in ground or fresh water can be toxic to newborns, young, or pregnant animals and can cause algal blooms resulting in so called aquatic "dead-zones."

NOx (NO and NO_2): Nitrogen oxides known as NOx emissions are listed by the U.S. EPA as criteria air pollutants. These are produced during combustion, especially at high temperatures (e.g., in motor vehicles and industrial facilities) and are precursors to ground-level ozone and fine particle pollution. NOx gases are also harmful to human health.

Ozone: An atmospheric gas that is present in low concentrations throughout the Earth's atmosphere. Ozone blocks damaging ultraviolet light from reaching the Earth's surface but also acts as a powerful but short-lived greenhouse gas. Ozone is a powerful oxidant with many industrial applications, but when present near ground level, it can cause respiratory damage in animals. Ozone from human sources comes primarily from fuel combustion.

Stand-alone LCA: Analyzes a single product to identify the life-cycle components that contribute most to environmental impacts, known as hotspots. System boundaries can also be geographic or refer to time frame.

System Boundaries: Identifies which life-cycle stages and which parts of associated systems are included in the LCA—where the system begins and ends.

System: In LCA, this refers to the production chain(s) being evaluated.

Appendices

Appendix A
Denitrification-Decomposition (DNDC) Modeling and LCA

The DNDC model performs process-based simulations of nitrogen and carbon dynamics in agroecosystems. Based on environmental drivers (inputs like soil characteristics, temperature, and precipitation data, crop characteristics, and crop management) the model predicts crop growth and yield, greenhouse gas emissions (such as carbon dioxide, methane, and nitrous oxide), and other environmental effects (like nitrogen leaching and runoff). DNDC is used widely around the world and has been tested against many field datasets in the U.S. and abroad. Incorporation of DNDC in the USDA-ARS, UC Davis Wine-Grape LCA, and the Wine Institute's Wine LCA will be complete in early 2013. DNDC modeling for these projects is contracted through Applied GeoSolutions. More information can be found at www.appliedgeosolutions.com.

Appendix B
Ongoing Agricultural LCA Project List and Selected Readings

California Wine and Wine-Grape Production LCAs

USDA-ARS at UC Davis: An Environmental Comparison of Wine-Grape Production using LCA. Cradle-to-gate, assessing an annual cycle of wine-grape production, and comparing regional differences and an array of management practices. Project funded by California Department of Food and Agriculture (CDFA) Specialty Crop Block Grants. Contact Kerri Steenwerth (kerri.steenwerth@ars.usda.gov) or Rachel Greenhut (rfgreenhut@ucdavis.edu) for further information. Research by Dr. Kerri Steenwerth and Rachel Greenhut (USDA-ARS, U.C. Davis Department of Viticulture and Enology), Dr. Alissa Kendall and Emma Strong (U.C. Davis, Department of Civil and Environmental Engineering).

The Wine Institute: California Statewide Wine LCA. Cradle-to-grave, assessing the environmental impacts of wine production across the state of California. Project funded by California Department of Food and Agriculture (CDFA) Specialty Crop Block Grants. More information at www.wineinstitute.org. Project led by Allison Jordan (The Wine Institute).

California Almond Production LCA

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Appendix C
LCA Interpretation and Application (Comparing a Particular LCA to Your Farming System)

The following list of questions can be asked in order to interpret the findings of an LCA and determine whether using recommended alternative practices may reduce the environmental impacts of one's own system.

1. Can you relate your system to the one being evaluated?

a. Do the system boundaries match yours?

b. Is your production system similar to one being evaluated?

i. Cropping system (e.g., annual vs. perennial)

ii. Size of operation

iii. Production methods (e.g., till vs. no-till)

iv. Material Inputs (e.g., fertilizer, compost)

v. Are there regional differences to consider (e.g., transport distances, climate)?

2. What hotspots are identified in the system studied?

a. Energy use, emissions, waste, resource use

i. Which life cycle stages contribute the most environmental impacts?

ii. Acquisition of raw materials, e.g., fertilizer

iii. Production and maintenance of capital goods, e.g., tractor

iv. Energy production, e.g., fuel

v. Production, e.g., growing the crop

vi. Transportation off the farm

b. Which of these hotspots may exist in my system as well?

c. Is my impact similar to that of the system studied, or is my system an improvement?

i. Can I measure these differences?

ii. Can I further reduce my impact in these areas?

iii. How can I use these improvements as part of my marketing strategy?

3. Does the LCA offer other options or alternatives to reduce the impacts related to the significant issues?

a. Would the alternatives work in my system?

i. Are they economically feasible?

ii. Are they technically feasible?

iii. Will they produce acceptable product?

b. If I apply the alternatives to my system, would the results be measurable (e.g., reduced fuel consumption)?

i. Is there opportunity for improved marketability of my product by reducing my impacts?

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www.attra.ncat.org/attra-pub/farm_energy

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