Greenhouse Gas and Energy Footprint (Life Cycle Assessment) of California Almond Production

Project No.: **11-AIR8-Kendall**

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Objectives:

This project calculates the life cycle greenhouse gas (GHG) emissions and life cycle energy, commonly referred to as the *carbon and energy footprint*, of California almond production from field production through hulling and shelling operations. The study was conducted in two parts – the first part characterized energy and emissions from nursery to farm-gate (harvested almonds) for one acre of almond orchard, and the second part from farm-gate through hulling and shelling operations. For part one of the analysis GHG emissions and energy are modeled over a 25-year period, the assumed productive lifespan of a block of almond orchard. For part two, annual energy and emissions were considered for a 'typical' hulling and shelling facility.

Calculating life cycle emissions and energy means that every phase of the life cycle is modeled, including nursery production of almond saplings, orchard establishment, field operations, chemical and material inputs to the orchard, field emissions, transportation, hulling and shelling, and the production of co-products and byproducts from the field (orchard biomass) and from processing (hulls, shells, and woody waste). At every life cycle stage the upstream impacts, which refer to the full supply chain energy and emissions, for all the inputs to the system, such as chemical manufacturing, fuel production, etc., are included.

Interpretive Summary

This analysis uses a life cycle assessment (LCA) approach to assess energy use and GHG emissions in almond production. The research was conducted in two stages: (1) orchard production of in-shell almonds, and (2) transport from the orchard, and hulling and shelling. The almond orchard production system is broken down into separate

modules analyzing external or custom operations (nursery production, orchard clearing, and harvest), in-field operations (equipment use, soil GHG emissions), and material inputs to the orchard (fertilizer and pesticide quantities). The LCA model (**Figure 1**) accounts for the separate life cycle phases within each of these modules, such as raw material extraction, processing, and manufacturing of a product; transportation of the product; and on-farm use of the product. The model also accounts for the variations in field operations, material and fuel use, biomass accumulation, and almond yield on a year-to-year basis. Year 0 includes orchard clearing and land preparation; years 1 and 2 include almond sapling production, planting, and orchard establishment; years 3 to 6 include increasing inputs, tree growth, and increasing almond yields; and years 7 to 25 mark tree maturity, constant inputs (fertilizer and pesticides), and constant yields. Throughout the orchard life span a percent of tree die-off and replacement is accounted for as well.

Data were collected from a variety of sources. The primary sources for direct material, chemical, and water inputs to cultivation, field operation types and times, and equipment types were:

1. UC Davis Department of Agricultural and Resource Economics (ARE) Cost and Return studies for almond production (Viveros, Freeman et al. 2003, Connell, Edstrom et al. 2006, Duncan, Verdegaal et al. 2006, Duncan, Verdegaal et al. 2006, Freeman, Viveros et al. 2006, Duncan, Verdegaal et al. 2011);
2. Surveys and interviews of growers, orchard managers, and custom operators;
3. Life cycle inventory databases (Ecoinvent Centre 2008, PE International 2009);
4. Geographic information systems (GIS) datasets and analytical tools;
5. Models for fuel combustion (California Air Resources Board 2007)

The sum of emissions and energy inputs for all of these components were calculated for each year of the orchard's lifespan. Emissions were separated by management category; pest management, nutrient management, and other management, which includes nursery sapling production, harvest, pruning, pollination, general maintenance, and irrigation, and also by input type. This differentiation allows identification of the major contributors to total GHG and energy footprints.

Energy use is presented as megajoules (MJ) or gigajoules (GJ = MJ×1000) per acre, and GHG emissions are presented in units of kg of carbon dioxide equivalent (CO_2e) per acre. CO_2e is a summary indicator for GHG emissions. The quantity of other GHGs [including nitrous oxide (N_2O), methane (CH_4), and sulfur hexafluoride (SF_6)] is normalized to the quantity of CO_2 by multiplying by their respective global warming potentials (GWPs), which results in units of mass of CO_2e (Intergovernmental Panel on Climate Change 2007).

Based on current modeling results, and baseline assumptions for co-product utilization, one acre of almond production is responsible for approximately 44,345 kg CO_2e emissions and credits of 34,257 kg CO_2e, resulting in net emissions of 10,088 kg CO_2e over the 25 year lifetime of an orchard. On an energy basis, one acre of almond production is responsible for approximately 689 GJ of energy use and 281 GJ of energy credits, resulting in net energy consumption of 407 GJ. On a per-lb basis for almond kernels, net emissions are 0.23 kg CO_2e and net energy use 9.3 MJ. Results are subject to change as ongoing calculations and revisions are underway, particularly with respect to carbon sequestration and energy credits.

Approximately 24% of CO_2e emissions and 37% of energy use are associated with irrigation, the largest single contributor to annual energy demand based on a statewide weighted average. Approximately 43% of CO_2e emissions and 26% of energy are attributable to nutrient management, the largest contributor to annual CO_2e emissions. **Figure 3** in the main body of this report shows the breakdown in energy and GHG emissions for all stages and operations.

These results reflect a number of modeling advancements since the last annual report. The following list describes the most significant ones:

1. Improved detail and precision in estimating irrigation water and energy use.
2. Improved detail and precision in calculating biopower generated from almond orchard waste.
3. Improved detail and precision in calculation of almond orchard biomass accumulation over the orchard productive lifespan.

Carbon credits from prunings and removed orchard blocks used in electricity cogeneration plants in the Central Valley represent a potential credit of up to 77% of total CO_2e emissions. That is, the total offset CO_2e from fossil fuel-based electricity generation that *could be replaced* by biomass-based electricity generation is about 77% of the total CO_2e emissions from the almond production system. The total possible energy generated from biomass is about 40% of the total energy consumption of the system.

Carbon sequestered in trees and soils is not considered at this time, because it is assumed to be temporary. However, ongoing analysis might change this as more data is available and as the potential for biochar (a byproduct of gasification systems that can recover energy from biomass) to sequester carbon is further explored. The potential for biomass from almond orchards to generate electricity and increase soil carbon under some conditions indicate that the almond production industry in California could *potentially* become carbon neutral or carbon negative, particularly if growers target adjustments to the most energy and GHG-intensive stages of the production system, and take advantage of potentially high value uses of co-products.

Material and Methods:

LCA is a well-developed, comprehensive method for estimating and analyzing the environmental impacts of products and services. LCA analyzes a product from 'cradle-to-grave', i.e., from raw material extraction through production and use, to waste management and disposal. Here, the analysis begins at the nursery that produces almond saplings and ends after hulling and shelling.

We use a process-based LCA approach, which directly measures and tracks material and energy flows through each of the phases in the life cycle of the product. Our LCA methodology conforms to the standards of the International Organization for Standardization (ISO) 14040 series on LCA, with the exception of peer review. A peer reviewed journal article will be developed and serve as a surrogate for an ISO peer review process.

A standard LCA framework consists of the following distinct steps:

1. Goal and scope definition, which includes defining the system boundary and functional unit of analysis.
2. Life cycle inventory, which includes identification and quantification of all inputs at each stage of the life cycle included within the system boundary.
3. Impact analysis - in this study, GHG emissions at each stage of the life cycle are characterized using GWPs into CO_2e.
4. Interpretation, which occurs throughout the analysis and in the discussion and conclusions of the results.

Goal and scope definition

The goal of this project is to establish a life cycle GHG emissions and energy inventory for CA almonds. In addition, we identify operations and inputs that contribute the most to total emissions over the almond production and processing life cycle; so-called emissions 'hotspots'. Finally, we estimate the potential credits to the almond production system for generating co-products that offset energy production from fossil fuels by generating biomass for electric power generation, and by producing feed and bedding for livestock.

For the nursery to farm-gate part of the study, the modeled system is one acre of representative almond orchard for the typical productive lifespan of an almond tree, 25 years. The lifespan is divided into categories that reflect different input demand and growth: years 0 through 6 which include orchard clearing, land preparation, orchard establishment and tree growth and maturation (at year 7), years 7 through 25 where tree maturity and maximum yield are reached and treated identically in the model. The area of orchard modeled is assumed to be established on land previously occupied by an almond orchard, and will be replaced with almond orchard at the end of its productive lifespan. No changes in land use type are considered. Flood, drip, and microsprinkler irrigation systems are modeled.

The second part of the study includes transport of harvested almonds to a hulling and shelling facility, and the hulling and shelling operations. Those operations are modeled based on process fuel and electricity use only.

The study's system boundary (**Figure 1**) includes:

1. Emissions from material and energy flows from external operations (fuel and agrochemical manufacture, orchard clearing, nursery tree production, and harvest);
2. Combustion emissions from operations in the field;
3. Soil emissions from fertilizer application;

4. Emissions from the transport of materials and equipment to the orchard as well as transport of biomass to cogeneration plants;
5. Transport of in-shell harvested almonds to hulling and shelling facility;
6. Hulling and shelling operations.

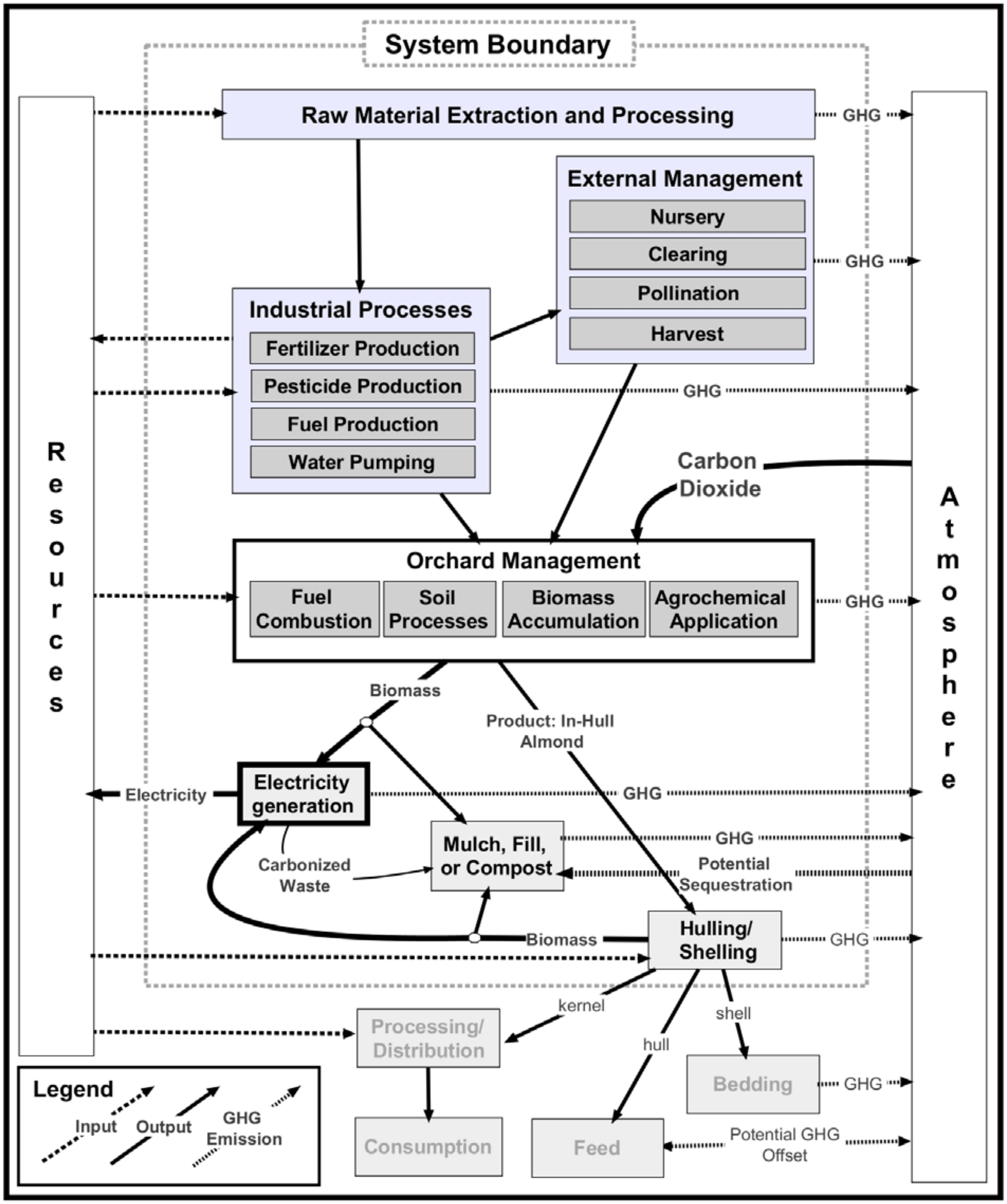

Figure 1. LCA System Boundary and Flow Diagram for California Almond Production.

System Definition and System Boundaries

The inputs to the almond production system can be divided into two categories: energy and materials. To calculate life cycle energy use, the upstream burdens of producing the energy resource or fuel are included. The study ends at the hulling and shelling facility. Additional processing and distribution of almond products is not included.

Equipment manufacturing and construction of buildings are excluded from the system boundary of this study as well, which is consistent with the treatment of long-term capital investments in other LCA studies. Agricultural equipment lasts a relatively long time, and may have multiple uses and so is unlikely to have a major impact on the results of this analysis; however, inclusion of equipment manufacturing may be analyzed in a future project. The end-of-life (recycling/disposal/reuse) of materials is included only for orchard biomass and hulls and shells, which may be directed either to cogeneration plants for production of electricity, used for mulch or fill, or as bedding or feed (for hulls and shells). The exclusion of packaging and packaging disposal for inputs (i.e. pesticides, fertilizers, etc.) is not expected to be significant for the accuracy of the model.

Functional Unit

The functional unit of this LCA is a mass of almond kernel, typically reported as one kilogram (kg) or one pound (lb). The functional unit of analysis is not the same as the modeling unit of analysis. Orchard production is *modeled* based on a single acre of almond orchard assessed over a 26 year time horizon for all inputs and outputs. The results of the 26-year per-acre modeling are then converted to kilograms and pounds of in-shell almonds by dividing through by total lifetime yield. Yield is not constant over the orchard lifespan: it is zero in years 0 through 2, increases from years 3 through 6, and remains stable from years 7 through 25. In turn, emissions per kilogram yield will not be constant year-to-year, so averaging over the orchard lifespan is required.

The functional unit can easily be converted to nutritional units, such as calories of food energy, grams of protein, or another measure of nutrition. This conversion allows comparison of the life cycle energy and emissions of almonds to other food products; however, these conversions are challenging since none is representative of all of the nutritional value of a particular food. We do not convert the functional unit to nutritional value in this report, nor do we compare results to other food products.

Allocation

Allocation is the process by which environmental flows associated with a system are divided among multiple products or services (i.e. co-products) generated from a single production process. The ISO14040 LCA standards (Technical Committee ISO/TC207-Environmental Management 2006) favor avoiding allocation calculations by subdividing the production system; assigning each production step or input to a particular co-product. This is rarely possible, especially for agricultural systems where inputs that benefit different parts of a plant cannot be clearly distinguished. Alternatively, allocation can be avoided by expanding the system boundaries to include all the co-products, though in practice this approach is implemented as ‘displacement’ or ‘substitution’.

These terms refer to a process where the production system is credited with *avoiding production or displacing substitutable products in the market*. This process is often challenging for agricultural systems, since co-products usually substitute for other co-products (i.e. almond shells used as bedding substitute for rice hulls used as bedding). When neither subdivision nor substitution is viable, then the standards recommend allocation based on the physical properties of co-products, such as mass or energy content, or lastly based on their economic value.

In contrast to ISO recommendations, some researchers have argued that economic allocation is the best approach, since it reflects the drivers for a business (Ekvall and Finnveden 2001, Guinée, Gorrée et al. 2002), and a physical basis of comparison may not properly reflect the purposes of a production system.

In this study both displacement and economic allocation are used. Co-products from the orchard include orchard waste biomass from non-productive trees and prunings. There are a number of potential fates for these materials including mulching and incorporation in the field, burning (though this is highly restricted), or removal and combustion for electricity. For the first two cases no carbon sequestration or co-product value is considered. In the last case where electricity is generated, co-products are handled using the displacement method. This is done by assuming that electricity generated from almond orchard waste displaces electricity from the average California grid electricity fuel mix.

Economic allocation was used in two of the sub-modules of the almond production LCA model, nursery production and pollination. In both cases data limitations and practical limitations prevented other methods for handling co-products.

For almond sapling production, total nursery inputs and GHG emissions were allocated to almond saplings based on the percentage of total gross nursery income from almond sapling sales. In the case of pollination, a previous LCA of US beekeeping and honey production conducted by the PI's research team was used as a data source to infer the energy and emissions associated with pollination based on economic allocation.

Allocation of hulling and shelling operations to co-products (hulls and shells) were calculated using the displacement method based on the possible fates for their use which included feed, livestock bedding, and electricity generation. Thus, displacement of fossil fuels for co-products used in electricity generation as well as displacement of cattle dietary components (roughage) is included.

Life Cycle Inventory (LCI)

LCI data quantify energy and material inputs as well as emissions for inputs to the system. Most LCI data used in the model come from published academic literature, the Ecoinvent database (last updated in 2011), the GaBi Professional database (last updated in 2011), and the U.S. LCI database (last updated in 2011) accessed through the GaBi 4 software (Ecoinvent Centre 2008, PE International 2009). The Ecoinvent and GaBi databases are proprietary international databases that tally cradle-to-grave environmental impacts of a large array of commonly used and internationally traded industrial materials, products, and natural resources such as oil and gas.

U.S. data were used where available, but European datasets were used when no U.S. data were available; this was particularly true for pesticide production. Some error may be introduced due to this substitution as European manufacturing standards and regulations differ from those in the US, but it is unlikely to make a significant difference to the overall results of the study due to the relatively small contribution from pesticides on total results.

LCI data for California-specific electricity production and truck freight transport were developed using datasets from the GaBi professional database and the appropriate fuel and technology mixes for the state of California.

Data Sources and Models

UC Davis Cost Studies

UC Davis *Cost and Return* studies for various commodities, including almonds, are generated by the UC Davis Department of Agricultural and Resource Economics (ARE) and UC Cooperative Extension. They involve collection of data from growers, orchard managers, and Cooperative Extension farm advisors through survey, interview, and focus groups. Ideally, they provide a picture of the typical nutrient, pesticide, fuel, and water inputs, equipment use patterns, and annual yields for an orchard system under a particular irrigation scheme (flood or microsprinkler) in a particular region (Sacramento Valley, San Joaquin Valley North, San Joaquin Valley South). Custom operations are reported simply as costs, so operations, equipment, and inputs associated with custom operations are not reported. This required that surveys and interviews be conducted to characterize custom operations.

The general practice for generating cost and return studies is to enumerate all likely expenses that could theoretically be incurred in commodity production. Thus, not every grower uses all the listed inputs or processes in a given year. For this reason, UC Davis *Cost and Return* studies are likely to represent an overestimate for the number of inputs and processes conducted for a given acre of production in a given year. Despite this, they are used in the current LCA model to provide baseline values for inputs and yields. Continued data collection and interviews with growers and orchard managers can help further refine the values derived from these studies.

Survey and Interview

Additional data were obtained through surveys administered to growers and orchard managers, custom harvest operators, orchard clearing operators, nursery operators, and hulling and shelling facilities. In some cases, in-person interviews were conducted to collect data on specific aspects of an operation, particularly equipment use and the time needed for various tasks. Survey response rates have been low, though a sufficient number were obtained to include each of the key operations included in this analysis. In some cases, such as nursery production, only a few operators exist within the state, and surveying even one or two of them captures a large segment of the industry.

Hulling and Shelling Operations

Five hulling and shelling facilities were surveyed. They provided information on energy consumption during operations and the mass and fates of co-products. These data were used to generate a weighted mean value for energy and fuel use per kilogram of almond kernel produced. The following co-product information was gathered in the surveys (**Table 1**):

Table 1. Co-product annual mass and fate: Weighted average for 5 surveyed shelling and hulling operations

Co-Product	Fate	Mass (kg)	% by Mass
Meats	Handler	24,330,652	31.6
In-shell	Handler	1,902,324	2.5
Hulls	Feed	37,984,437	49.3
Hash	Feed	385,006	0.5
Shell	Energy	10,992,532	14.3
Woody Biomass	Energy	637,894	0.83

Table 2 shows the average direct energy consumption for hulling and shelling activities per kg of kernel produced. This is *total* facility energy, meaning that energy has not yet been allocated among almond kernel and other co-products.

Table 2: Weighted average direct energy use in hulling and shelling operations

	Electricity	Propane	Diesel	Gasoline	Total
MJ per kg of kernel produced*	0.55	0.023	0.011	0.0086	0.59
*note, this is unallocated - meaning this is total average energy used in the facility - co-product allocation is not included in the calculations					

Electricity Generation from Orchard Biomass

Biomass removed from orchards can be used to generate electricity in one of the many biopower facilities in California. Assuming that 95% of biomass from orchard clearing is used for electricity production in biomass-fueled generation facilities (estimates obtained from interviews and literature search), our model estimates that approximately 156,776 MJ electricity per acre can be produced over the 25 years of an almond orchard's productive lifespan, avoiding up to 47,052 kg CO_2e/ac emissions from typical grid electricity generation in California. These estimates represent likely electricity generation potential based on interview of orchard industry representatives and published literature, and verification requires further analysis and data from individual biomass-fueled power facilities in California. Additional description of this process is provided in the discussion of carbon credits from co-products.

Irrigation Energy Model
Since the last report, significantly more detail and precision has been developed through the development of a geo-spatial model. The geo-spatial model created for this project maps irrigation systems and sources of irrigation water using detailed California-specific datasets and ArcGIS software, for a much greater level of precision. The model includes data on upstream energy required for irrigation water in different locations. Geospatial data on almond acreage throughout the Central Valley were overlaid with maps of the three main hydrologic regions of the Central Valley and the California Aqueduct system. Data on irrigation energy for groundwater pumping (Burt, Howes et al. 2003) and energy use at various aqueduct pumping stations (Klein and Krebs 2005) as well as data from the California Almond Sustainability Program on almond irrigation methods (Almond Board of California., unpublished data) were used to generate weighted mean electricity use for almond orchard irrigation throughout the Central Valley.

Combustion Emissions Model
Fuel combustion emissions were modeled using the OFFROAD software developed by the California Air Resources Board (CARB). This software models fleet emissions by geographic region, and thus may introduce errors based on inaccurate fleet population estimates. For this reason, both the OFFROAD software and a “bottom-up” model derived from OFFROAD emissions factor data and equipment engine data were used to estimate hourly fuel consumption and emissions. OFFROAD-based modeling was used to estimate emissions of CO_2, N_2O, and CH_4 for equipment operation. **Appendix 1** of this report includes detailed descriptions of the OFFROAD model and calculation methods used in the LCA model.

Field Emissions Model
While a variety of air emissions may occur from agricultural fields and soils, in this model only N_2O emissions are tracked. The model allows for two types of N_2O estimates which are referred to as Tier 1 and Tier 2 by the IPCC (Intergovernmental Panel on Climate Change 2006). Tier 1 IPCC methods are based on global average emissions factors that linearly relate the quantity of nitrogen fertilizer applied to soils to N_2O emissions, irrespective of climate, soil, irrigation, or crop type. Tier 2 methods are intended to better reflect the local conditions and require that regionally-specific emissions factors based on field testing or other data be used to generate emissions factors. Tier 2 N_2O emission factors were generated using relevant information based on California conditions and practices for N application rates, irrigation methods, climate and soil. Additional descriptions of the N_2O emissions estimation methods used in the model are available in **Appendix 2**.

Transportation Model
Transport distances were obtained through personal communication with chemical manufacturing company representatives, material safety data sheets, and a grey

literature search to determine where active ingredients and final formulations are manufactured. Shipping routes were calculated with Google Distance Calculator (Google Inc. and Daft Logic 2011) and primary literature (Kaluza 2010). The US freight rail network was mapped in Google Earth Pro, and distances by various routes to the main rail hubs of California were calculated. Average truck transport distances from rail hubs to almond orchards were also calculated in Google Earth Pro, as were average transport distances from nurseries, orchard clearers, and other custom operations. LCI data for fuel use and emissions due to various modes of freight transport were obtained from GaBi US databases (PE International 2009).

Global Warming Potential (GWP)

GHG emissions are reported as CO_2e emissions by multiplying the mass of a GHG by its GWP. The relative GWP values of the GHGs accounted for in this study (CO_2, CH_4, N_2O, and SF_6) are presented in **Table 3**. The GWPs vary for different time horizons due to the lifespan of individual GHGs in the atmosphere. The LCA model includes time horizons of 20 and 100 years (GWP_{20} and GWP_{100}, respectively). Total GWP potential for each time horizon was calculated according to Equation 10.

Equation 10. Global warming potential, where m_x is total mass of a GHG "x" emitted, and GWP_x is the IPCC value for global warming potential of the GHG "x" over time horizon "t".

$$GWP_{total} = \sum m_x \times GWP_{x,\, t}$$

Table 3. IPCC global warming potential values for common GHGs for 20 and 100 year time horizons (t=20 and t=100)

IPCC AR4 GWP Values (CO_2 equivalents)		
	GWP_{20}	GWP_{100}
CO_2	1	1
N_2O	289	298
CH_4	72	25
SF_6	16300	22800

Co-Product Credits and Carbon Sequestration

The almond production system can potentially receive credit for generating byproducts or co-products if they are put towards economic use or sequester carbon for long time horizons, of 100 years or more. Most byproducts from almond production do find economic use. For example, as shown in **Table 1** hulls typically become cattle feed, shells are used for bedding and electricity generation, and prunings and cleared trees may be used for electricity generation. Each of these secondary uses can offset the production of other materials and fuels (and their accompanying energy and GHG emissions) that would otherwise be required. Carbon sequestration in the soil and tree biomass may also be a source for credits to the production system, though they are currently not included in calculations due to uncertainty in the level and persistence of carbon sequestration.

As a perennial cropping system, almond orchards accumulate significant woody biomass over their productive lifespan that will be removed either through orchard clearing or pruning activities. Data were collected for biomass removed from cleared orchards – a sample of clearing jobs from 62 different locations in the Central Valley and representing a total of more than 2000 acres was used in estimation of average biomass removed from an acre of almond orchard at the end of its productive life. Published values (Wallace 2007) were used to estimate average prunings removed per acre as well. A logistic growth model was applied to distribute biomass accumulation from year one through year 25, based on the above clearing data and data collected from nursery operators.

The percent of cleared biomass that is used in electricity generation is set at 95%, based on data collected from clearing operators. Though in theory prunings can be used for electricity generation, the baseline model assumes that they are mulched or burned in-field. Emissions and energy use from biomass transport from orchard to biopower plant were also accounted for.

Geospatial data for orchard acreage as well as known biopower plant locations were used to determine the mean distance traveled in the Central Valley to deliver biomass to energy facilities. Travel distance and mass calculations for hulling and shelling facility residues were also calculated and used to generate transportation-related emissions. Transport energy and emissions were then subtracted from the potential credits from displaced average electricity generation using LCI data for truck freight transport.

LCI data for the typical California electricity generation mix and biomass energy content (California Biomass Collaborative 2005, Bioenergy Feedstock Information Network (BFIN) 2010) data were used to calculate the amount of fossil-fuel based energy production offset by the use of almond waste biomass for electricity generation. Biomass energy facility emissions data were used to calculate potential carbon content of facility waste (biochar), which has the potential to sequester carbon over long time horizons. However, this is not reported as a credit in the current results due to high uncertainty in its persistence over time.

A range of potential biomass fates were used to calculate a maximum and minimum for potential co-product credits. These fates included in-field burning of orchard clearing and pruning waste biomass, mulch (incorporation of green biomass/chips into soil), and electricity generation at a biopower plant. For hulls and shells additional potential fates included use as cattle feed and livestock bedding for hulls and shells respectively. However the following values are used as the baseline for typical production:

- Orchard woody biomass: 95% goes to energy production, 2.5% is mulched, and 2.5% burned in-field.
- Pruning waste: 50% is mulched and 50% is burned in-field.
- Processing woody biomass: 90% goes to energy, and 10% mulched.

- Shells: 50% goes to energy, and 50% bedding.
- Hulls: 100% goes to dairy cattle feed. Feed offset is generated by assuming displacement of roughage from the cattle diet, which is primarily composed of forage, hay, and straw; dried and stored.
- For all scenarios, no long-term carbon sequestration was considered.

LCA Computer Model

The LCA model is developed in Microsoft Excel. The model is broken down by year, with data for equipment operation hours, equipment type, agrochemical input, and transportation miles entered by row. LCI data for production and transportation emissions as well as model outputs for combustion and field emissions are then calculated based on input mass, operation time, and transportation distance. We also disaggregated the results in the following two mutually exclusive ways: first by management category (pest management, nutrient management, other operations) in order to determine what areas of orchard management contribute the most to total emissions, and second by input type, namely energy (e.g. fuel and electricity) versus material (e.g. agrochemical) inputs. External operations (pollination, nursery production) were modeled exogenously and LCI data added in the appropriate years.

Results and Discussion

This analysis quantified GHG emissions and energy use on a yearly basis for one acre of "typical" almond orchard and per pound of kernel produced (**Table 4** and **Figure 2**). Improvements to the model since our last report include a weighted average for different irrigation types used throughout California almond orchards, and spatially explicit energy use for irrigation water delivery in different regions. This had significant effects on total energy use for almond production. Also important were the displacement and sequestration credits generated, this significantly changed the outcomes for CO_2e emissions. Assumptions regarding energy and chemical inputs as well as model variables are essentially unchanged from the previous report.

We found that over the 25 year productive lifespan of an acre of almond orchard, the mean GHG emissions are 44,345 kg CO_2e/acre, reduced to 10,088 kg net CO_2e/acre when carbon credits are accounted for. **Table 4** includes outcomes for energy and emissions per acre (over 25 years) and pound of kernel.

Table 4. Energy and Emissions for Almond Production (Nursery through Hulling)

	Over 25-years per Acre		Per lb of kernel	
	No Credits	With Credits	No Credits	With Credits
GHGs (kg CO2e)	44,345	10,088	1.01	0.23
Primary Energy (MJ)	688,591	407,561	15.7	9.3

Figure 2 shows the breakdown in energy and GHG emissions by operation. Approximately 24% of CO_2e emissions and 37% of energy use are associated with irrigation, the largest single contributor to mean annual energy demand. Approximately 43% of CO_2e emissions and 26% of energy are attributable to nutrient management, the largest contributor to annual CO_2e emissions. This is due to the energy and fossil fuel intensive nature of fertilizer production, and N_2O emissions from orchards induced by nitrogen fertilizer application. **Figure 2** also shows that processing does not play a large role in energy and GHG emission compared to orchard production, comprising about 4% of CO_2e emissions and approximately 6% of energy consumption.

Figure 3 provides an alternative illustration of GHG emissions (and credits) for the production system from year 1 until orchard removal. In these figures year 0, the year that the previous orchard is removed, is not included, but the electricity credit for the removed orchard is accounted for by amortizing over the life of the orchard. **Figure 3** shown annual fluxes (emissions or sequestration/avoided emissions) for the orchard system. The emissions spike in year 12 is attributable to irrigation system replacement.

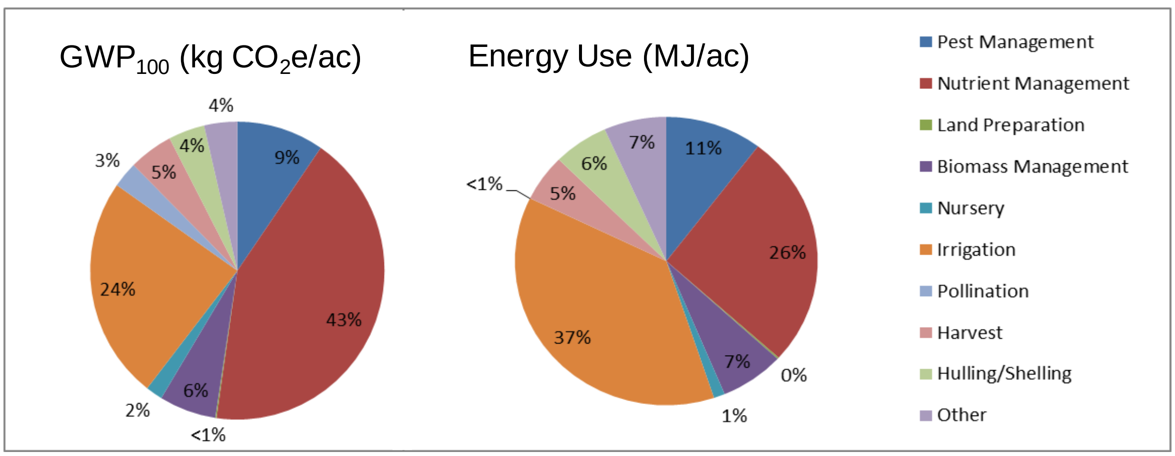

Figure 2. Breakdown of GWP_{100} and Energy by Operation

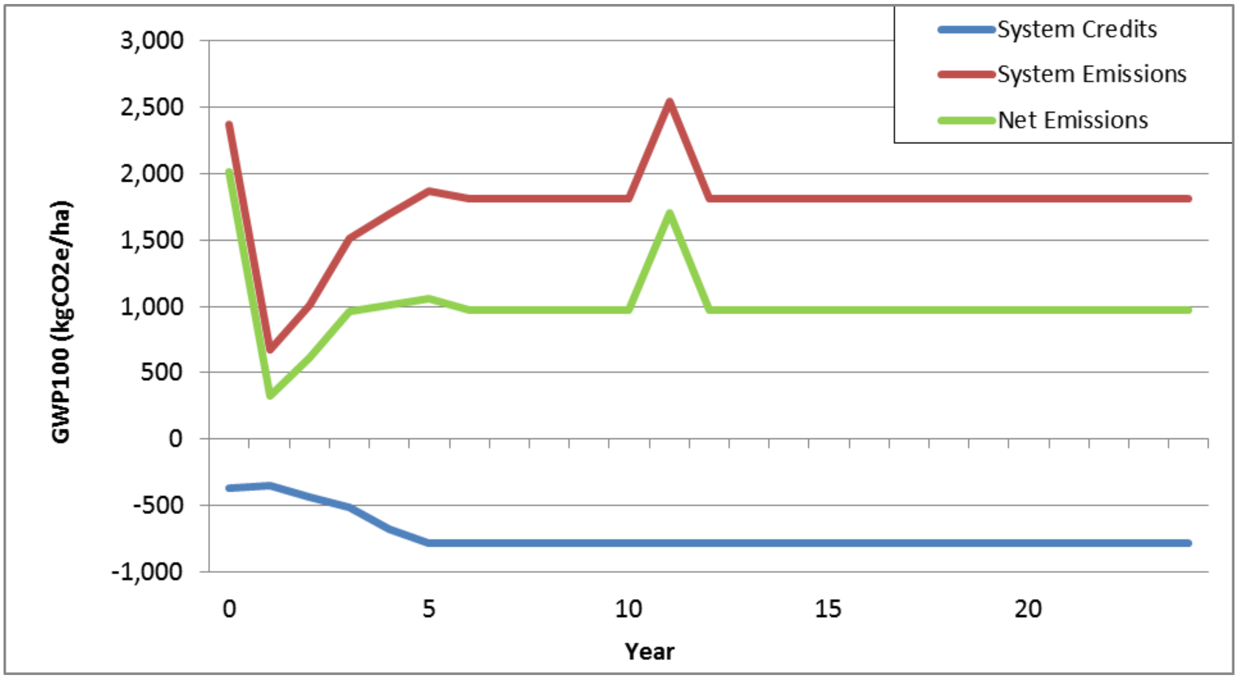

Figure 3. Annual GHG Emissions (in CO_2e) for the Almond Orchard Production System. **Note that credits for electricity generation from orchard clearing biomass are amortized over the lifespan of the orchard.*

We estimated best-case and worst-case scenarios for theoretical maximum carbon sequestration and offset potential (**Figure 4**). Worst case assumes 100% of orchard clearing and pruning waste is burned in field and all processing waste is mulched (i.e., used as fill). The best case assumes 100% of waste from clearing, pruning, and processing is directed to energy production.

No sequestration credits was assigned to mulched biomass, nor were trees assigned sequestration credits in any of the scenarios, so the only carbon credits generated are from offsets in electricity generation. These results show that improved utilization of almond waste biomass (prunings, cleared trees, hulls and shells) for electricity generation has the potential to further improve the environmental performance of almond production systems. Moreover, if some long-term sequestration does occur, such as from increasing soil carbon levels or durable uses of wood, then additional sequestration credits might be achievable.

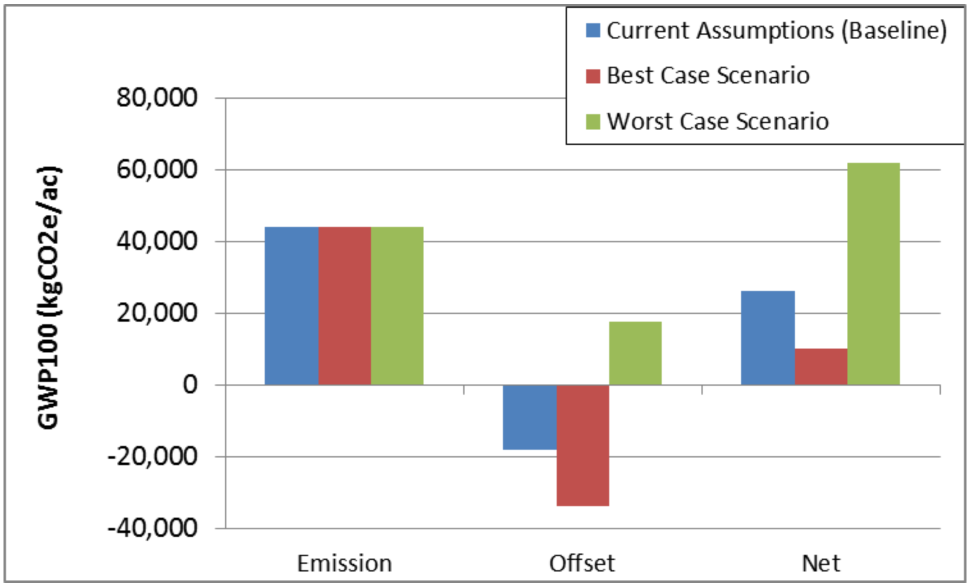

Figure 4. Possible GHG and energy credits from cogeneration and sequestration.

Opportunities

Methods and rules for generating carbon sequestration credits require evidence of 100-years or more of sequestration. Current data and understanding of sequestration from incorporating chipped biomass into soils, or long term sequestration of carbon in tree root systems simply does not permit assigning a carbon credit. However, with additional research this could change.

An additional opportunity for carbon sequestration credits is biochar. Biochar is generated during pyrolysis of biomass; pyrolysis is one technology that can be used for biopower generation. When incorporated into soils, some biochar has shown persistence for thousands of years. The biochar research community is highly active, and as new data becomes available, this too might provide additional opportunities for increasing carbon credits for the almond industry.

Research Effort Recent Publications

Marvinney, Kendall A., Brodt S. (2013). Life Cycle Assessment of Long-Lived Perennial Cropping Systems: Biomass-Based Energy Production and Orchard Greenhouse Gas Footprints in California. ISIE 2013 Conference: Strategy for a Green Economy. Ulsan, Korea.

Marvinney E., Kendall A., Brodt S., Zhu W. (2011). Greenhouse Gas and Energy Use Footprint of California Almond and Pistachio Production. IERE LCA XI Conference: Instruments for Green Futures Markets. Chicago, IL.

Marvinney E., Kendall A., Brodt S., Zhu W. (2011). Life cycle assessment of energy and greenhouse gas emissions for California almond production. ISIE 6th International Conference on Industrial Ecology: Science, Systems and Sustainability. Berkeley, CA.

Marvinney E., Kendall A., Brodt S. (2011). Greenhouse gas footprint and environmental impacts of the California nut industry: an LCA approach. UC Davis, Interdisciplinary Graduate and Professional Symposium. Davis, CA.

Appendix 1. OFFROAD Model and Equipment Emissions Calculations

The bottom-up model was constructed in Microsoft Excel, using the following parameters obtained from OFFROAD databases for particular equipment and engine types: maximum engine horsepower, load factor, and emission factors (EFs). EFs in this model indicate emissions of a particular GHG per horse-power hour (g/hp*hr), or emission mass per unit energy, and were given for total hydrocarbons (THC), carbon monoxide (CO), nitrogen oxides (NO_x), particulate matter (PM), and carbon dioxide (CO_2). Further emissions factors for additional GHGs were derived according to equations 1 and 2 (California Air Resources Board 2007). This model also calculates hourly fuel consumption for different engine types, according to equations 3 and 4. Most of the variables and constants used in these equations were obtained from OFFROAD datasets, except for energy efficiency (EE), which was assigned a value of 0.30. Accepted values for combustion engine efficiency range from 0.30 – 0.35 (Oak Ridge National Laboratory 2011).

The fuel consumption and emissions outputs of this bottom-up model were compared to values for emissions and fuel consumption based on the top-down population-based results of the published OFFROAD model, as well as to an alternative calculation based on fuel carbon content rather than fuel energy content. Values from all three models were checked against published data, grey literature, and personal communications dealing with fuel consumption and emissions, and the model output most closely matching accepted values was used. In most cases, this value was that obtained through bottom-up calculation based on energy content, or the official OFFROAD model output.

<u>Equation 1.</u> OFFROAD emission factor for nitrous oxide (N_2O). N_2O is derived from engine NOx emissions. Equation 1 applies to gasoline engines only, because data for diesel engines were not yet available. Therefore, Equation 1 was used as an approximation for calculating diesel N_2O emissions.

$$EF_{N_2O} = 0.458 * EF_{NO_x}{}^{0.5332}$$

<u>Equation 2</u>. OFFROAD emission factor for methane (CH_4). EF_{CH4} is derived as a fraction of total hydrocarbons (THC) and varies by fuel type. Fuel type coefficients (CF_{fuel}) are given in **Table A1**.

$$EF_{CH_4} = EF_{THC} * CF_{fuel}$$

Table A1. Fuel type coefficients for OFFROAD CH_4 emission factor calculation. C2/C4 refers to 2- and 4-stroke natural gas, and G2 and G4 refer to 2- and 4-stroke gasoline, respectively.

Fuel Type	Model Year	CF_{fuel}
Diesel		0.0755
C2/C4		0.7664
G2	≥2004	0.0572
	1996-2004	0.0558
	<=1995	0.0774
G4	≥2004	0.0572
	1996-2004	0.0558
	<=1995	0.1132

Equation 3. OFFROAD emissions by engine activity. Equation 3 is used to calculate emissions from various engine and fuel types based on maximum horsepower (HP), hours of engine activity (t), and load factor (LF). Load factor is a unit-less ratio that describes the proportion of maximum HP translated to useable energy under field conditions. The LFs from the OFFROAD database are derived from population-level data and may not accurately reflect conditions in the orchard, and may be adjusted such that fuel consumption and emission values more closely match published data.

$$\boldsymbol{Emission = t * HP * LF * EF}$$

Equation 4. Hourly fuel consumption (HFC). Equation 4 is derived from the energy content of specific fuels (E_{fuel}, **Table A2**) – by determining the amount of energy in fuel necessary to produce a given HP for 1 hour, accounting for engine efficiency (EE), load factor, and engine activity time (t). EE is estimated at 0.30 – typical range for internal combustion engines is from 0.30 – 0.35 (Oak Ridge National Laboratory 2011).

$$\boldsymbol{HFC = \frac{HP * LF * t}{EE * E_{fuel}}}$$

Table A2. Fuel energy content (Oak Ridge National Laboratory 2010)

Fuel Energy Content		
	BTU/ gallon	MJ/ liter
Gasoline	115000	32
Diesel	130500	36.4

Appendix 2. N_2O Emissions Estimation Method

The IPCC methods divide N_2O emission from managed soils into two parts, the direct and indirect emissions. The pathway of the direct N_2O emission is the N_2O released directly from the soils to which synthetic N fertilizer is added. The indirect emissions occur through the pathways of (i) volatilization of NH_3 and NO_X and the subsequent re-deposition of these gases and their products NH_4^+ and NO_3^- to soils and waters; and (ii) leaching and runoff of N, mainly as NO_3^-. For California almond orchards, as neither leaching nor runoff is a major issue, we did not take account for the second pathway. Hence our calculation includes the following two parts: (i) direct N_2O emissions, (ii) indirect N_2O emissions from volatilization, through NH_3 and NOx (**Figure A1**). N_2O is emitted from soils of almond orchards through the processes of nitrification and denitrification. In nitrification, N_2O is produced as a gaseous intermediate while ammonium is oxidized to nitrate under aerobic conditions. In denitrification, N_2O is produced as a by-product from a process where nitrate is reduced to nitrogen gas under anaerobic conditions (Intergovernmental Panel on Climate Change 2006).

Two of the major drivers for soil N_2O genesis are the availability of inorganic nitrogen (N) in the soil, and the soil aeration conditions (or soil moisture content). The former is mainly controlled by fertilization practices and the latter by irrigation and precipitation events. In the Central Valley, as precipitation is not common during the growing season, it contributes less to N_2O genesis than irrigation. Hence fertilization and irrigation are closely related to N_2O emissions from the soils of California almond orchards.

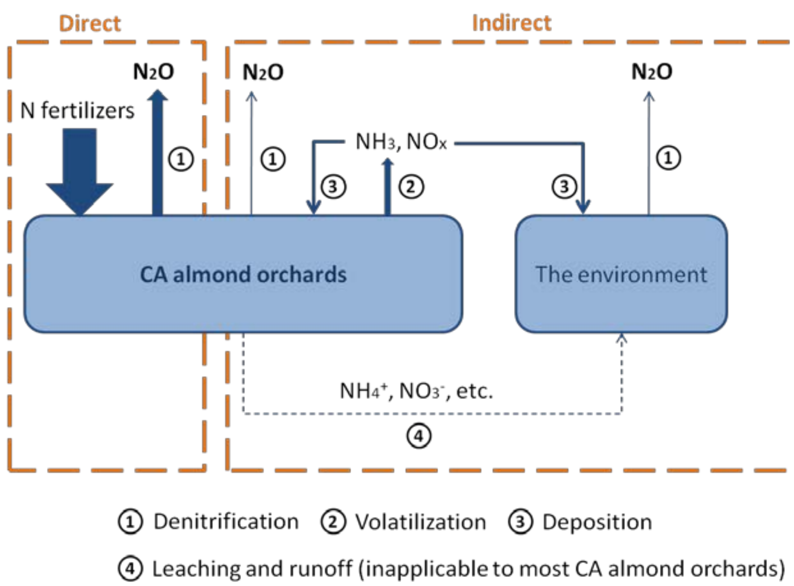

Figure A1. Pathways of direct and indirect N_2O emissions from California almond orchards

The N_2O emission factors (EFs) and emission rates (ER) of the three irrigation types are listed in **Table A3** below.

Table A3. N_2O emission factors (EFs) by irrigation type

Irrigation type	EF of direct N_2O (uncertainty) EF_{Direct}	EF of indirect N_2O through NH_3 EF_{NH3}	EF of indirect N_2O through NOx EF_{NOx}
	N_2O-N/N applied	N_2O-N/N applied	N_2O-N/N applied
Flood	0.35%	0.066%	0.0012%
Microsprinkler	0.33%	0.043%	
Drip	0.31%	0.047%	

The EFs of direct N_2O for microsprinkler and drip irrigation systems were measured in the field by Alsina and Smart in 2010 (Alsina and Smart 2010). N_2O was sampled from the wet area around the emitters of conventional drip and microsprinkler irrigation systems for four fertilization events during the growing season. Additional N_2O emission data were obtained for drip irrigated almonds, including measurements in tree rows (where N fertilizer is applied) as well as tractor rows (where no fertilizer or irrigation water is applied) (DeCock, unpublished data). These data, along with published material on the effect of water-filled pore space on N_2O emissions from orchard soils (Smart, Alsina et al. 2011), were used to estimate N_2O emissions from soil based on the effective wetting area of different irrigation methods and the total amount of nitrogen added in fertilizer. The emissions factors calculated in this way are shown in **Table A3** above.

No field data are available for estimating N_2O emissions from fields that use flood irrigation. Therefore, the EF for flood irrigation was calculated based on directly measured data from drip and microsprinkler systems and the assumption of 100% wetting of the orchard floor. That is, a greater area of orchard floor in flood systems is assumed to experience conditions favorable to N_2O release, resulting in a higher emission factor (**Table A3**). This is an improvement over previous estimates which used IPCC data on intermittently flooded rice paddies, which although they may experience a similar irrigation regime, are generally located on much heavier soils, and experience vastly different rates of gas flux due to the ability of rice plants to transmit gases from the subsoil to the atmosphere.

The EFs of indirect N_2O through NH_3 were converted from the field-measured data (Krauter, Potter et al. 2000). Krauter et al. reported that the NH_3 EFs of almond orchards for flood, buried drip and microsprinkler irrigations are 6.6%, 0.5%, and 0.0%, respectively. Assuming that 1% of the N in the volatized NH_3 is eventually released as N_2O in the soils and water of other ecosystems (Intergovernmental Panel on Climate Change 2006), we approximated that the indirect N_2O EFs through NH_3 for flood, drip and microsprinkler irrigations are 0.066%, 0.005% and 0%, respectively.

The ER of indirect N_2O through NOx was converted from field measured data (Matson, Firestone et al. 1997). Matson et al. reported that the weighted mean hourly NOx flux is 0.64 g N/ha/hr, measured from drip and flood irrigated almond orchards in San Joaquin Valley. Their measurements were taken within two weeks following four scheduled fertigations (Matson et al., 1997), capturing the peaks of soil NOx emissions during the growing season. Hence we assumed that this hourly NOx flux represented each of the 24 hours of the 14 days after the four fertigation events in that year, or 1344 hours per year. Thus we approximated that the NOx ER is 860 g N/ha/yr. Assuming that 1% of the N in the volatized NOx is eventually released as N_2O in the soils and water of other ecosystems, we used 8.6 g N/ha/yr as the indirect N_2O ER through NOx in our calculation for the generic condition of California almond orchards, regardless of the irrigation type.

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