Greenhouse Gas and Energy Footprint of California Almond Production

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1. Objectives

The objectives of this project are to assess the climate impact and energy use of almond production in California, from nursery to farm gate for one acre of almond orchard, as defined by the sum of greenhouse gas (GHG) emissions created and energy used throughout the life cycle of almond production. This includes the chemical and material manufacturing phase, field emissions phase, and transportation phase, and excludes processing and consumer-related phases. In order to make this assessment, the following environmental flows are quantified over a 25-year period (the assumed productive lifespan of a block of almond orchard):

1. Total (GHG) emissions – kilograms of carbon dioxide (CO_2), nitrous oxide (N_2O), methane (CH_4), and sulfur hexafluoride (SF_6).
2. Total energy inputs – megajoules (MJ) of fossil and renewable energy.
3. Biomass accumulation – mass of CO_2 equivalents (CO_2e) stored in almond tree biomass.
4. Carbon sequestration in orchard floor soil.

Research supported by the Almond Board of California for 2011-2012 will calculate energy and emissions associated with transportation and processing of almonds, which, when combined with results from the study reported here, will enable us to calculate the energy and GHG footprint for one pound of almond kernels and additional units of analysis, such as nutritional calories.

2. Interpretive Summary

This analysis uses a life cycle assessment (LCA) approach to assess energy use and GHG emissions in almond production. The almond 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 flow (fertilizer and pesticide quantities). The LCA model (**Figure 1**) accounts for the separate life cycle phases of each of these modules (manufacturing, transportation to the farm, and on-farm use), as well as the variations in each operation and component on a year to year basis from year 0 (clearing and land preparation), through years 1 and 2 (nursery production, planting, orchard establishment), years 3-6 (increasing yields and inputs with tree growth) and years 7-25 (tree maturity and steady inputs).

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 UC Davis Department of Agricultural and Resource Economics (ARE) Cost and Return studies for almond production (Viveros et al. 2003; Connell et al. 2006; Duncan et al. 2006; Duncan et al. 2006; Freeman et al. 2006, Duncan et al. 2011); surveys and interviews of growers, orchard managers, and custom operators; life cycle inventory databases (Ecoinvent Centre 2008; PE International 2009); geographic information systems (GIS) analysis; and various models for combustion (California Air Resources Board 2007) and field emissions.

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 (including nursery sapling production, harvest, pruning, pollination, general maintenance, and irrigation), and also by input

type, specifically fuel and energy versus agrochemicals. This differentiation allows identification of the major contributors to overall GHG and energy footprints.

Energy use is presented as megajoules per acre, and GHG emissions are presented in units of kg of carbon dioxide equivalents (CO2e) per acre. The unit CO2e is used in order to standardize across the four different GHGs of significance in this study - carbon dioxide, nitrous oxide, methane, and sulfur hexafluoride. CO2e is calculated by multiplying the quantity of each GHG emitted by its respective global warming potential (GWP) (Intergovernmental Panel on Climate Change 2007).

In general, nutrient management (including manufacturing, transport, application, and soil N_2O emission) represents the largest single contributor to overall GHG emissions at about 32% of total CO2e (see **Figure 4**). However, the combined CO2e emissions of other management operations contributed a total of about 61% of total CO2e. This is largely due to the energy and fossil fuel intensive nature of harvest, pollination, and irrigation operations. Pest management contributed only about 6% of total CO_2e emissions.

Although the GHG and energy footprint of almond production is relatively high, at about 2370 $kgCO_2e$/acre and 16700 MJ/acre, respectively, we found that possible credits to the system for electricity generation offsets and carbon sequestration are potentially high as well. Carbon credits from burning prunings and removed orchard blocks in electricity cogeneration plants in the Central Valley represent a potential credit of up to 138% of total CO_2e emissions. That is, the total offset CO_2e from fossil fuel-based electricity generation that is *replaced* by carbon-neutral biomass-based electricity generation is about 38% greater than the total CO2e emissions of the system. The total possible energy generated from biomass is about 34% of the total energy burden of the system. Alternatively, possible credits for sequestration of CO_2 in biomass were also examined – for example, when prunings or cleared trees are chipped and mulched back into soil on or off-site.

Theoretical maximum sequestration credits represent about 82% of total system CO2e. This assumes that 100% of carbon stored in biomass is sequestered in soil, a percentage that is not achievable due to decomposition of mulched biomass. However, it is possible to sequester a significant proportion of the carbon present in prunings and removed trees through charcoal production and incorporation into soil. For this reason, possible sequestration credits were included in the analysis.

These findings indicate that the almond production industry in California can potentially become carbon neutral or carbon negative with adjustments to the most energy and GHG-intensive sectors of the production system. As the primary data sources (UC Davis Cost/Return studies) for input quantities in this analysis tend towards overestimation, it is expected that as further data is collected from individual growers and operations throughout the Central Valley, many individual operations may be found to be carbon neutral or negative.

3. Materials and Methods

3.1 Life Cycle Assessment Methodology
The calculations presented here are based on a life cycle assessment (LCA) of almond production. 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 materials extraction through production and use, to waste management and

disposal. In the case of almond production, the analysis is from "nursery-to-farm gate." This scope includes manufacturing and shipping of agrochemicals, fuels, materials, and equipment, as well as air emissions from the combustion of fuels and field emissions.

We primarily used 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 calculated in terms of carbon dioxide equivalents (CO_2e).
4. Interpretation of impacts analysis.

3.1.1 Goal and scope definition
The goal of this project was to establish a life cycle inventory for CA almond production, and to estimate the GHG emissions and energy associated with almond production activities. In addition, we identified operations and inputs that contribute the most to total emissions over the almond production life cycle; so-called 'hotspots'. Finally, we estimated the potential effects of carbon sequestration in biomass and soil, including credits to the almond production system for offsetting energy production from fossil fuels by generating biomass for electric power generation.

The modeled system is one acre of representative almond orchard for the typical productive lifespan of an almond tree. The lifespan is divided into categories that reflect different input demand and growth: year 0 (orchard clearing and land preparation) through year 7 (tree maturity and maximum yield) which includes changing operations and agrochemical inputs; and years 7-25 are treated identically and reflect typical operations from tree maturity to the end of productivity. It is assumed that the acre of orchard modeled was established on land previously occupied by an almond orchard, and will be replaced with almond orchard at the end of its productive lifespan. Both flood and micro-sprinkler irrigation systems were modeled.

The study's system boundary (**Figure 1**) includes (1) emissions produced by 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, and (4) emissions from the transport of materials and equipment to the orchard as well as transport of biomass to cogeneration plants.
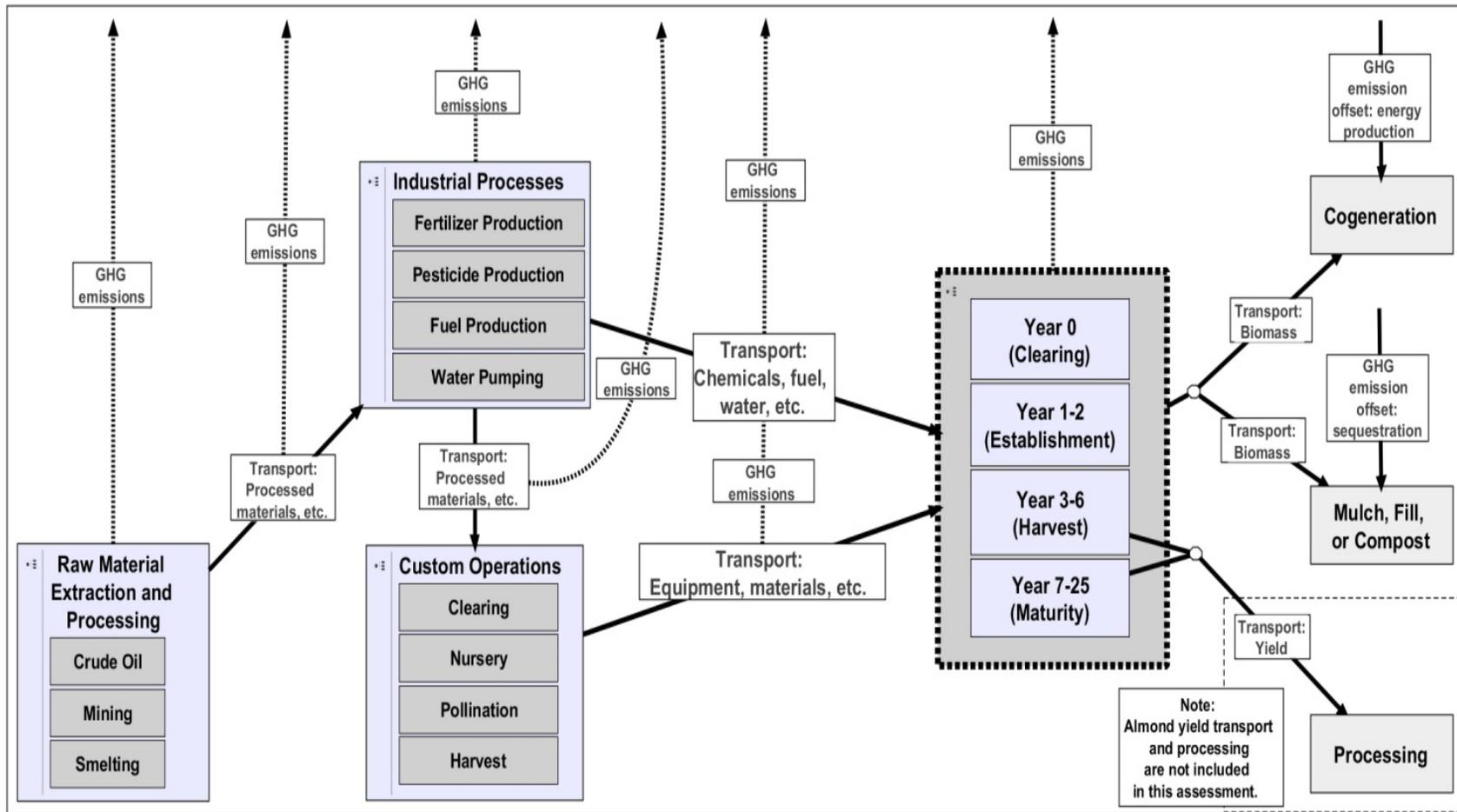
Figure 1. LCA System Boundary and Flow Diagram for California Almond Production.

3.1.2 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 stages in the almond life cycle are summarized as orchard clearing and preparation, nursery production, orchard establishment, tree growth, steady-state production, processing, and distribution. Processing and distribution are excluded from this study and will be analyzed in next year's research.

Equipment manufacturing and construction of buildings are excluded from the system boundary of this study, 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, capital investments in equipment will be analyzed in a future project. The end-of-life (recycling/ disposal/ reuse) of all materials is included only for biomass, which may be directed either to cogeneration plants for production of electricity or used for mulch or fill. Some frequently reused durable materials, like drums and barrels for agrochemicals, are assumed to have small lifetime environmental burdens and thus are not modeled in the study.

3.1.3 Functional Unit
The functional unit of this analysis is a single acre of almond orchard assessed over a 26 year time horizon for all inputs and outputs. In the forthcoming 2011-2012 research, this unit will be converted to inputs and emissions per kilogram and pounds of almonds by dividing through with yield data in kilograms per acre per year, which increases from year 3 – 6 and remains stable thereafter. In turn, emissions per kilogram yield will be converted to inputs/ emissions per calorie of food energy. In this way, we will be able to compare almond production to other land use systems, other agricultural production systems, and other food products.

3.1.4 Allocation
Allocation is the process by which environmental flows associated with a system are divided among various outputs from a single industrial process (i.e. co-products). The ISO14040 LCA standards (Technical Committee ISO/TC207 2006), favor avoiding allocation calculations by subdividing the system based on the different products produced, or expanding the system boundaries to include all flows associated with co-products. When data are not available for either of these two options, then the standards recommend allocation based on the physical properties of co-products, such as mass or energy content. However, if allocation is pursued on a mass-basis for almond orchard co-products, for example, the vast majority of the GHG and energy footprint would be assigned to orchard waste biomass. This allocation does not reflect the primary economic driver of almond orchard production systems; the production of almonds. An alternative method is economic allocation: that is, burdens are allocated according to the relative economic value of a given output. By allocating based on the relative value of co-products, the motivations that drive production are better reflected.

In this study, orchard waste biomass (non-productive trees and prunings) are considered a waste product, and therefore no upstream GHG or energy burden is allocated. Allocation of burdens between hulls, shells, and kernels is not addressed in this study, as this is considered part of the processing phase and is outside the system boundary. However, economic allocation was used in two of the sub-modules of the almond production LCA model: nursery production and pollination.

In the case of nursery production, total nursery inputs and GHG emissions were allocated to almond saplings based on the percentage of total gross nursery income due to almond sapling

sales. In the case of pollination, a previous LCA of US honey production that has not yet been published was used as a data source to infer the energy and emissions associated with pollination. The honey LCA examined beekeeping operations throughout the continental US and estimated total GHG and energy burdens associated with honey as a percentage of gross apiary income. The other major component of apiary income is derived from pollination services, and a similar economic allocation was made to estimate the GHG and energy burdens associated with pollination.

3.1.5 Life Cycle Inventory (LCI)

LCI data quantify energy and material inputs as well as emissions for a variety of materials including diesel and gasoline fuel, agricultural chemicals, plastics, and other agricultural inputs such as manure. U.S. data was used where available, but was substituted with European datasets (Ecoinvent Centre 2008) in some cases, mostly 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 low impact of pesticides on overall agrochemical-related emissions (see results section).

Most LCI data 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. The U.S. LCI database is a similar, but open access database, created by the National Renewable Energy Laboratory, and focuses on materials and products produced in the U.S. LCI data for California-specific electricity production and truck freight transport developed using GaBi 4 (Kuczenski 2010a, Kuczenski 2010b).

3.2 Data Sources and Models

3.2.1 UC Davis Cost Studies

UC Davis cost and return studies for various commodities, including almonds (Klonsky et al 2006, 2008, 2011), are generated by the UC Davis Department of Agriculture 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 group. 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 micro-sprinkler) in a particular region (Sacramento Valley, San Joaquin Valley North, San Joaquin Valley South), and omit information on operations, equipment, and inputs associated with custom operations.

The general practice of the ARE Department in the case of cost and return studies is to enumerate all likely expenses that could theoretically be incurred in commodity production. In practice, not every grower uses all listed inputs and they are only applied as needed rather than annually. For this reason, UC Davis cost and return studies likely represent an overestimate of total inputs and energy use on a per-acre basis. They are used to provide baseline input and yield data which will later be refined through data collected directly from a variety of growers and orchard managers.

3.2.2 Survey and Interview

Additional data were obtained through surveys administered to growers and orchard managers, custom harvest operators, orchard clearing operators, and nursery operators. In some cases, in-person interviews were conducted to collect data regarding specific aspects of an operation, particularly equipment used and time needed for various tasks. Survey response rates have been low (1-2 respondents for each survey) but data collection is ongoing and further responses are expected. Though we expect to continue collecting data, sufficient surveys were obtained to include each of the above operations 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 portion of the total industry.

3.2.3 Combustion Emissions Model

Fuel combustion emissions were modeled using the OFFROAD software package 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.

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.

__Equation 1.__ 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.

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

Equation 2. *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 1**.*

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

Table 1. 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.*

$$Emission = t * HP * LF * EF$$

Equation 4. *Hourly fuel consumption (HFC). Equation 4 is derived from the energy content of specific fuels (E$_{fuel}$, **Table 2**) – 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).*

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

Table 2. Fuel energy content (Oak Ridge National Laboratory 2010).

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

3.2.4 Field Emissions Model

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.

In this study, we estimate N_2O emissions from soils using relevant information based on California conditions and practices for N application rates, irrigation methods, climate and soil were incorporated into the calculation. Regional N_2O emissions factors, with the irrigation method as a variable, were developed based on these factors. We adopted the IPCC Tier 2 method to quantify the N_2O emissions from almond orchard soils (Intergovernmental Panel on Climate Change 2006). Tier 2 IPCC methods require that region-specific emissions factors based on field testing or other data are available, while Tier 1 IPCC methods are based on global average emissions factors.

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 NOx 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 2**).
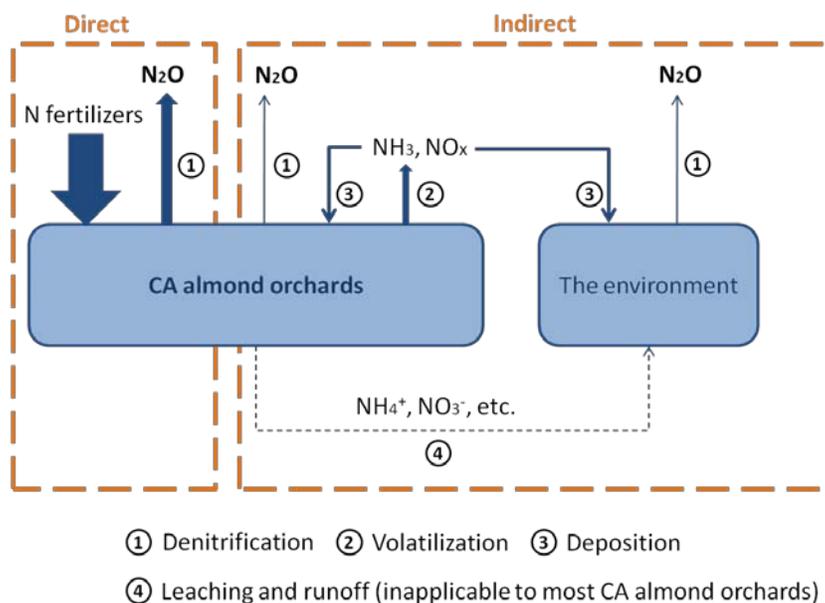
Figure 2. Pathways of direct and indirect N_2O emissions from California almond orchards

The N_2O emission factors (EFs) and emission rate (ER) of the three irrigation types are listed in **Table 3** below.

Table 3. N_2O emission factors (EFs) and emission rate (ER) of the three irrigation types

Irrigation type	EF of direct N_2O (uncertainty) EF_{Direct}	EF of indirect N_2O through NH_3 EF_{NH3}	ER of indirect N_2O through NOx EF_{NOx}
	N_2O-N/N applied	N_2O-N/N applied	g N_2O-N/ha/yr
Flood	0.3% (0.6%)	0.066%	
Micro-sprinkler	0.25% (0.05%)	0%	8.6
Drip	0.63 (0.09%)	0.005%	

The EFs of direct N_2O for micro-sprinkler 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 micro-sprinkler irrigation systems for four fertilization events during the growing season.

No field data are available for estimating N_2O emissions from fields that use flood irrigation. For the small portion of almond orchards that use flood irrigation, the EF for direct N_2O was taken from the Intergovernmental Panel on Climate Change (2006). As the flood irrigation applied in

almond orchards in California is intermittent, we adopted the EF for N_2O emissions from N inputs to flooded rice because no flood irrigation emissions factors exist for orchards.

The EFs of indirect N_2O through NH_3 were converted from the field-measured data (Krauter et al. 2000). Krauter et al. reported that the NH_3 EFs of almond orchards for flood, buried drip and micro-sprinkler 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 micro-sprinkler irrigations are 0.066%, 0.005% and 0%, respectively. The ER of indirect N_2O through NOx was converted from field measured data (Matson 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.

3.2.5 Transportation Model
Transport distances were obtained through personal communication with chemical manufacturing company representatives, material safety data sheet (MSDS), and grey literature search to determine where active ingredients and final formulations are manufactured. Shipping routes were calculated with Google Distance Calculator (Google, Inc et al. 2011) and primary literature (Kaluza et al 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).

3.2.6 Global Warming Potential
It is necessary to report GHG burdens in terms of global warming potential (GWP) in order to account for the variable effect of different types of GHGs. This was done according to IPCC Fourth Assessment Report (AR4) guidelines (IPCC 2007). Carbon dioxide (CO_2) is considered the baseline in terms of global warming potential, and all other GHGs are reported in terms of CO_2 equivalents (CO_2e) – for example, one molecule of N_2O is the equivalent of 275 molecules of CO_2 on a 20 year time horizon. 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 4**. The GWPs vary for different time horizons due to the lifespan of individual GHGs in the atmosphere. This study addresses 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 GHG "x" emitted, and GWP^t_x is the IPCC value for global warming potential of GHG "x" over time horizon "t".*

$$GWP^t_{total} = \left(m_{CO_2} * GWP^t_{CO_2}\right) + \left(m_{CH_4} * GWP^t_{CH_4}\right) + \left(m_{N_2O} * GWP^t_{N_2O}\right) + \left(m_{SF_6} * GWP^t_{SF_6}\right)$$

Table 4. 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	275	296
CH_4	62	23
SF_6	15100	22200

3.2.7 Carbon Credits

The almond production system can potentially receive carbon credits from the use of various by-products (also known as "co-products") in other economic sectors. For example, hulls typically become cattle feed, shells are used for bedding and electricity generation, and prunings and old trees can also be used for electricity generation. Each of these secondary uses can offset the production of other materials or processes (and their accompanying GHG emissions) that would otherwise be required. Because the system boundaries for this current study end at harvest and do not encompass almond hulling and shelling (which will be included in the 2011-2012 study), we limit our current analysis of possible credits to carbon sequestration in the soil and tree biomass and electricity generation from woody biomass. 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. 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 energy content in a kilogram of dry wood was obtained from published sources (Wallace 2007), and a conservative estimate for cogeneration plant conversion efficiency of 0.25 was used to determine possible electricity generation offsets. To calculate the GHG offset value of electricity cogeneration, the total MJ of energy obtainable from the biomass removed from the orchard each year (with orchard clearing calculated for year zero and amortized over the remaining 25 years) were calculated and then the equivalent emissions from the typical California grid electricity generation mix were subtracted from the yearly total. This calculation is based on the assumption that biomass burning emissions in cogeneration are carbon neutral, as all emitted carbon was originally drawn down from the atmosphere via photosynthesis. The percent of clearing biomass going to cogeneration was set at 95%, based on data collected from clearing operators. The amount of prunings going to cogeneration was set at 50%, based on personal communication and published literature (Wallace 2007). Emissions from biomass transport from orchard to cogeneration plant were included in this calculation.

Possible carbon credits for sequestration were calculated based on the carbon content of wood (~45%, variable in different tissues). This was based on data collected from peach, a close relative of almond (Grossman and Dejong 1995). Carbon mass was converted to CO_2 mass, and subtracted from the yearly emissions total (under the assumption that 100% of biomass

carbon could be sequestered over a 20-100 year timeline). It should be noted that sequestration credits cover only CO_2, whereas fossil-fuel electricity offset credits account for other GHGs as well. Thus, the overall GWP credit for electricity offsets is greater than that for sequestration. Sequestration was considered a mutually exclusive alternative to cogeneration offset, but under some conditions it may be possible to collect carbon waste from biomass burning and return it to the soil as agrichar or agricultural charcoal (Wallace 2007).

In this case, both offset and sequestration credits could be applied to the system. Further investigation is needed regarding the technology and practices of biomass cogeneration plants in California in order to determine the degree to which this occurs. Published data (Kroodsma and Field 2006) was used to generate an estimate of orchard floor soil carbon accumulation per year under typical California orchard management conditions, which was also included in carbon credits for sequestration. This value may be an overestimate, especially if a significant amount of carbon is lost as CO_2 during orchard removal and land preparation for planting. Further investigation and analysis will be necessary to elucidate the role of orchard floor management in carbon sequestration.

3.2.8 Life Cycle Assessment Model
All of the above models contribute to the LCA model for almond orchards which was generated in Microsoft Excel. The LCA 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. Global warming potentials are calculated in separate columns from in-row emissions data. All results are then summed. 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 elsewhere by similar means and emissions data added in the appropriate years.

4. Results and Discussion

This analysis quantified GHG emissions and energy use on a yearly basis for one acre of "typical" almond orchard (**Figure 3, Table 5**). It attempts to use the most conservative values available for energy, fuel and chemical inputs available from UC Davis cost and return studies, particularly Duncan et al 2011. Further analyses will make explicit comparisons between different irrigation systems and account for the prevalence and distribution of each general type of irrigation system in almond orchards. Assumptions regarding energy and chemical inputs as well as model variables (enumerated in section 3.2) were made to be as conservative as possible, to avoid underestimation of energy and GHG burdens. We found that over the 25 year productive lifespan of an acre of almond orchard, the mean annual GHG emission is about 2370 kgCO2e/acre, and the mean annual energy use is about 16700 MJ/acre (**Table 5**).

Approximately 32% of CO_2e emissions and 54% of energy use are associated with nutrient management, the largest single contributor to mean annual CO_2e emissions. This is due to the energy and fossil fuel intensive nature of fertilizer production and the large quantities applied in tree nut production. The various management activities included in "other management" collectively account for 61% of emissions and 29% of energy use (**Figure 4**). The largest contributors in this category over the lifetime of the orchard block are irrigation, harvest, and

pollination; although input-intensive nursery sapling production accounts for a large spike in emissions in year 1.

Figure 4 also shows that emissions are dominated by in-field operations (64% of total), whereas energy consumption is dominated by agrochemical input (65% of total), highlighting the role of combustion emissions as well as the energy intensive nature of agrochemical manufacturing. This is also visualized in **Figure 5**, which shows the percent of total burdens associated with each phase: manufacturing, field, and transport (as explained in section 3.2).

We found that if 95% of biomass from orchard clearing and 50% of biomass from pruning is utilized for electricity production in cogeneration plants (estimates obtained from interview and literature search), then 5720 MJ/ac of energy can be produced, avoiding 3280 $kgCO_2e$/ac emissions from fossil-fuel based power plants in California. This is visualized in **Figure 4** (blue bars) as negative values, and enumerated in **Table 6**.

Alternatively, we estimated theoretical maximum carbon sequestration potential in orchard soils based on published data regarding orchard floor management and carbon inputs (Kroodsma and Field 2006) and the carbon content of almond tree biomass (Grossman and Dejong 1995). Sequestration potential was calculated as a theoretical maximum value, which is not achievable in practice, and even with this optimistic assumption, sequestration contributed much less compared to cogeneration in terms of potential credits to the almond production system.

These results show that energy production from almond waste biomass (prunings and cleared trees) has the potential to further improve the environmental performance of almond production systems, and even make the almond industry carbon neutral or carbon negative if fully exploited. As an alternative where cogeneration is not a viable option, some credits to the system can be achieved by converting waste biomass to charcoal and incorporating it into the orchard floor or other soils.

The significance of these results is to highlight the fact that almond production systems in California have the potential to contribute to global CO_2 sequestration and carbon-neutral energy production. It is likely that many individual almond production operations where certain conditions for biomass-based electricity cogeneration (e.g., distance to cogen plants, cogen plant efficiency, volume of waste biomass utilized, net management burdens and yield, etc.) are met, may already be GHG negative. Further analysis based on data from individual operations, (including orchard clearing, orchard management, and cogeneration plants) is needed in order to refine these estimates, since what has been presented so far on cogeneration plants should be considered as preliminary results.

Table 5. Mean annual GHG emissions and energy use per acre over orchard lifespan. Note that total burdens are divided either by management type (pest, nutrient, other) OR by input type (fuel/electricity, agrochemical). Each of these categories summed equals the total burden.

|	Total		Management Type				Input			Possible Credit	
			Pest	Nutrient	Other		Fuel and Electricity	Agro-chemical		Co-generation	Sequestration
Energy (MJ)	1.67E+04		2.69E+03	9.13E+03	4.83E+03		5.62E+03	1.10E+04		-5.72E+03	*na*
GWP^{100} (kg CO_2e)	2.37E+03		1.48E+02	7.73E+02	1.45E+03		1.52E+03	8.54E+02		-3.28E+03	-1.95E+03
GWP^{20} (kg CO_2e)	2.57E+03		1.59E+02	8.13E+02	1.60E+03		1.67E+03	8.96E+02		-3.68E+03	-1.95E+03
CO_2 (kg)	1.71E+03		4.96E+01	4.24E+02	1.24E+03		1.26E+03	4.53E+02		-3.04E+03	-1.95E+03
N_2O (kg)	1.13E+00		7.85E-02	8.96E-01	1.69E-01		2.46E-01	8.98E-01		-2.63E-02	*na*
CH_4 (kg)	6.87E+00		3.42E-01	1.50E+00	5.03E+00		5.29E+00	1.58E+00		-1.03E+01	*na*
SF_6 (kg)	3.80E-05		2.29E-06	3.52E-05	5.40E-08		5.29E-07	3.75E-05		-1.43E-07	*na*

Table 6. Summary of net emissions and energy burden per acre: total burden plus maximum possible credit for cogeneration offset or sequestration.

|	Cogeneration	Sequestration
Energy (MJ)	1.09E+04	1.67E+04
GWP^{100} (kg CO_2e)	-9.11E+02	4.25E+02
GWP^{20} (kg CO_2e)	-1.12E+03	6.22E+02
CO_2 (kg)	-1.33E+03	-2.39E+02
N2O (kg)	1.10E+00	1.13E+00
CH4 (kg)	-3.43E+00	6.87E+00
SF6 (kg)	3.79E-05	3.80E-05
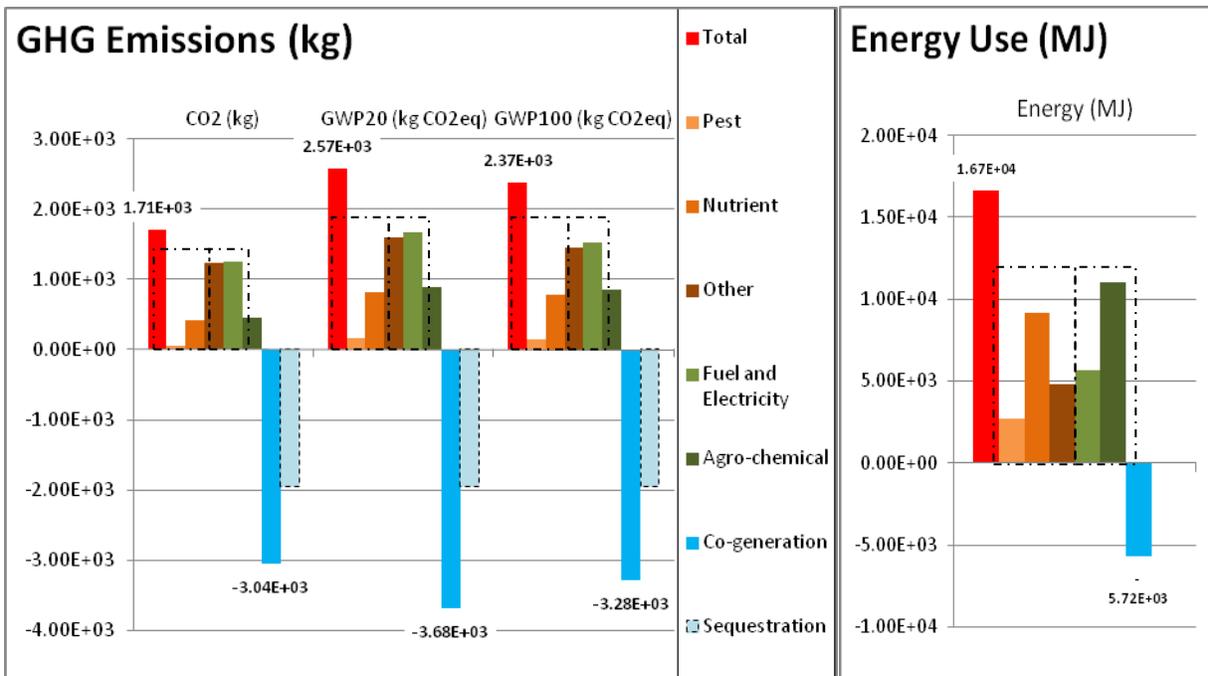
Figure 3. Mean annual energy and GHG flows per acre over orchard lifespan.

Note: emissions were divided in two ways (dashed box outline). First (in orange), by management category. Second (in green), by input type. Each of these subgroups represents a different method of subdividing total emissions (in red); i.e., the sum of values in either subgroup equal total emissions. Possible GHG credits are shown as negative values (in blue). The totals column (red) does NOT include estimates for credits. The credit for sequestration (dashed outline) represents a theoretical maximum based on almond biomass carbon content.
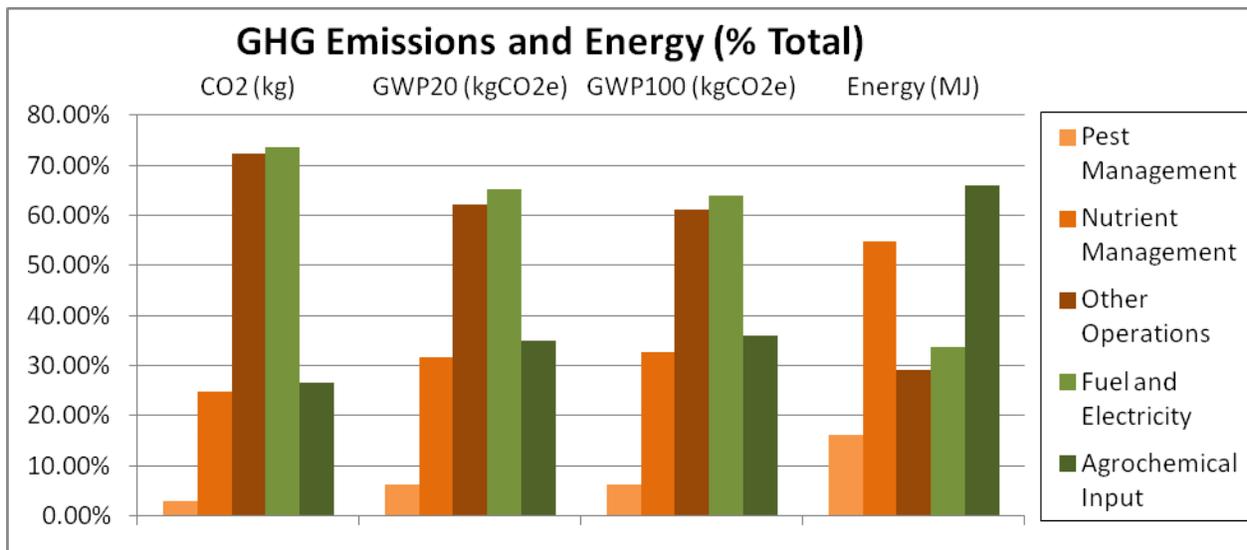

Figure 4. GWP and energy consumption per acre by category: percent of total.

Note that orange-colored bars show subdivision of the results broken down by management category, while green bars show subdivision of results by input type. Each of these two sets of bars sum to 100%, independently of the other set.
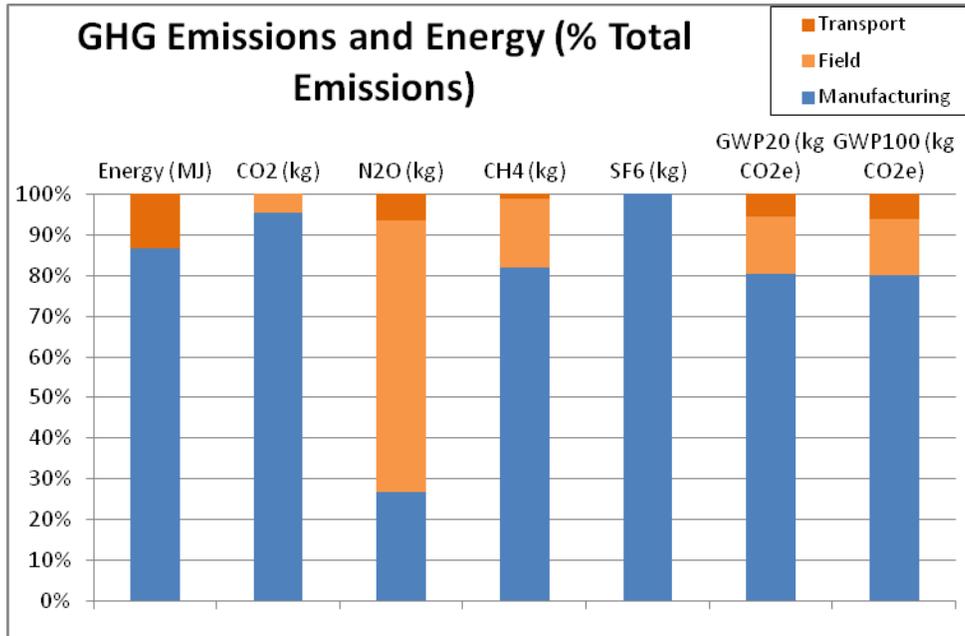
Figure 5. Percentage of GHG and energy flows associated with each phase of the almond production system. Manufacturing includes upstream raw material extraction, processing, and manufacturing phase. Transport includes transportation of materials and chemicals from place of origin to the orchard. Field includes combustion emissions from equipment and field emissions from fertilizer application.
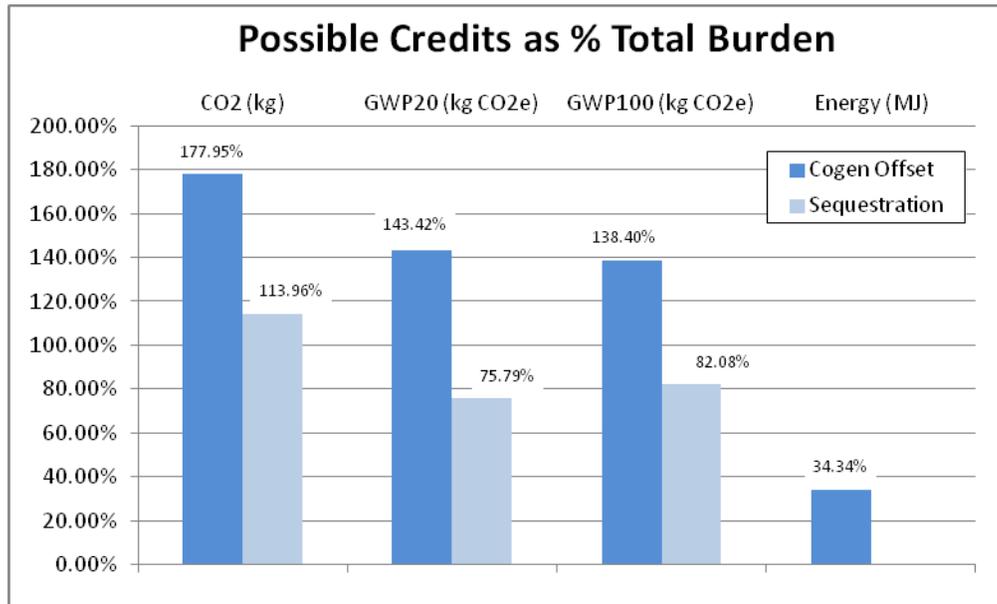
Figure 6. Possible GHG and energy credits from cogeneration and sequestration as percent of total energy and emissions.

5. Research Effort Recent Publications

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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.

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