LIFE CYCLE ASSESSMENT:
A TOOL FOR QUANTIFYING THE ENVIRONMENTAL IMPACTS OF FRESH AND DRIED PLUM PRODUCTION

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OBJECTIVE

Life Cycle Assessment (LCA) is a comprehensive approach for assessing the environmental impacts and resources used throughout the full life cycle of a system or a product, such as an orchard crop. LCAs typically account for the energy and environmental impacts of all stages of a product's life cycle, such as acquisition of raw materials, the production process, handling of waste byproducts, and more. To date, this life cycle model of dried plum production considers the quantity of irrigation water used specific to orchard location, energy and fuel required for pumping water, energy required to produce, transport, and apply fertilizers and pesticides, energy needed for harvest, transport, and post-harvest processing including drying.

By characterizing, quantifying, and interpreting the environmental flows from "cradle-to-grave," LCAs can play an important role in assessing the greenhouse gas (GHG) and pollutant emissions associated with agricultural products, which tend to be more dependent on regionally specific conditions and factors than industrial products. Importantly, LCAs can also identify "hot-spots" - opportunities along the production chain for reducing energy consumption and pollutant/ GHG emissions. The LCA approach can also identify and quantify potential GHG and pollutant reductions that occur in the production process. This dried plum model also includes estimates of carbon sequestration in orchard floor soils as well as avoided emissions from fossil-fuel based energy production from the use of orchard waste biomass as an electricity feedstock.

The life cycle perspective is also useful in avoiding problem shifting from one phase of the life cycle to another or from one environmental issue to another. For example, the use of synthetic nitrogen fertilizer accounts for a relatively modest portion of the total GHG emissions of field production for many crops when only considering on-farm operations and soil emissions of nitrous oxide (caused by adding nitrogen to the soil). However, when the energy-intensive manufacturing of the fertilizer is included as a stage in the analysis, the portion of GHG emissions attributable to synthetic nitrogen use can increase by 30-150%, typically making it one of the largest sources of total GHG emissions in the carbon footprint of many crops, and warranting much more attention in GHG reduction efforts.

Greenhouse gas tracking or "carbon footprint" LCAs have applications for growers, food manufacturers, and retailers interested in reducing the GHG emissions of their products. Growers might use LCA models to estimate total emissions and understand where their greatest emissions are occurring, as well as to estimate the effects of different farming practices. They may also be used in the future to help focus publicly funded GHG emissions reductions incentive programs such as farm bill conservation programs or California's cap-and-trade Greenhouse Gas Reduction Fund, or to demonstrate eligibility for market-based carbon offsets as these programs become available. Manufacturers, retailers, and commodity organizations can use LCAs on a farm-level or industry-wide basis for marketing, labeling, or certification purposes.

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PROCEDURE

Data on fresh and dried plum production were collected from a variety of sources. UC Davis Economic Cost/ Return Studies as well as some grower interviews provided generalized data on typical practices, equipment, and agrochemical inputs; the USDA NASS Cropscape dataset provides orchard location in the Central Valley; the California DWR provided data on surface water delivery infrastructure and groundwater depth; an orchard clearing company provided data on biomass removal; GaBi and EcoInvent provided life cycle-based data on resource use and pollutant emissions for various inputs and manufacturing processes; the CDFA provided yield and market share (of dried vs fresh plum) data; and the California Biomass Collaborative provided data on soil carbon accumulation in orchards and California biomass power plant locations and characteristics. Data on post-harvest processing and other external or contracted operations (nursery production, transportation, pollination, etc) were obtained from published literature, questionnaires, and interviews.

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The aerial image-based dataset for dried plum acreage and age generated by LandIQ provided improved assessment of the geospatial relationships between plum orchards and biomass and irrigation infrastructure in the Central Valley, as well as forming the basis for improved calculation and prediction of potential orchard clearing biomass use as an energy feedstock. Data from almond woodchip decay experiments undertaken by San Joaquin county farm advisor Brent Holtz were used to make a preliminary estimate of soil carbon storage potential under various orchard end-of-life biomass management practices. Cost Study data on fertilizer application rates were replaced with survey data from Prune and Plum Production in California (Lazicki, Geisseler, and Horwath 2016).

The above data were used to develop an LCA model of fresh and dried plum production in ArcGIS, Microsoft Excel, and R. This model sums the life cycle emission and energy use data for all inputs and processes occurring in fresh and dried plum production, treating each production year separately, from orchard establishment through maturity. Results are calculated on the basis of several functional units: per acre of orchard, per kilogram of fruit, and per nutritional calorie.

RESULTS AND CONCLUSIONS

In previous analyses, “nursery to farm gate” emissions and energy use were dominated by nutrient management – in particular by the production and application of nitrogen fertilizer. With the incorporation of more recent survey data (Lazicki, Geisseler, and Horwath 2016) on actual fertilizer application rates and percent of acres receiving fertilizer, the impacts from phosphorus application increased, but this was more than offset by a substantial decrease in emissions from nitrogen and potassium application. This reduced the estimate of environmental impacts from nutrient management, resulting in roughly equal impacts from irrigation, nutrient management, and biomass management (Fig. 1).

As in the previous iterations of this model, when the scope of analysis is expanded to “nursery to post-harvest gate”, energy use in post-harvest drying becomes the greatest contributor to overall environmental impacts (Fig. 1). This is also apparent when reporting results by life cycle phase: on-farm, off-farm, and transportation (Fig. 2). Greenhouse gas (GHG) impacts are favored for reporting in chart form both because this impact category relates directly to economic implications for the plum industry via California carbon markets, and because most other air pollutant emissions are roughly similar in pattern (but not magnitude) in industrial processes, making GHG emissions a good proxy for other pollutant emissions. Tables 1 and 2 show the full life cycle inventory including criteria air pollutants and acidification (as in acid rain), eutrophication (nutrient pollution in waterways), and smog-forming potential.

Quantification of temporary carbon storage in standing biomass of plum orchards and estimates of soil carbon accumulation indicate some potential for offset of these GHG impacts. In previous versions of this orchard LCA model, the use of biomass from orchard removal provided a significant offset of total on-farm GHG emissions. Results from almond and walnut orchard models indicate that adoption of certain biomass management practices such as the use of processing byproducts for on-site energy generation and the use of orchard clearing biomass for off-site energy generation can increase such offsets to the point where net orchard greenhouse gas impacts are close to zero or even negative (representing a net reduction in atmospheric greenhouse gas concentrations as a result of orchard production).

Organic walnut production is an example of an orchard production system analyzed using this LCA modeling procedure where post-harvest energy use (here, for refrigeration of nuts used in lieu of fumigation) represents the major driver of system impacts. In this case study, use of solar panels and walnut shell in on-site energy generation using a Biomax100 modular gasification system resulted in significant offset of fossil-fuel based energy and natural gas use, from on-site production of electricity and producer gas respectively. Given the importance of natural gas burning in plum drying operations, this indicates potential for a similar system operating on a plum pit feedstock to offset the impacts of plum post-harvest operations. Data on the gasification properties and energy content of dried plum pits was not available

Greenhouse gas and pollutant offsets from use of orchard clearing biomass for energy production have changed significantly since this model was first developed. The original iteration of this model assumed that about 95% of cleared orchard biomass was directed to biomass energy facilities and resulted in avoided fossil fuel-based emissions, based on personal communication with orchard clearing company representatives. Given plant closures and updated orchard location information (Fig. 4), this estimate was reduced to 74%, with a corresponding increase in burning (for firewood or in-field) and mulching biomass fates. As biomass energy facilities close, the distance for transport and likelihood of alternative biomass fates increase while the total potential for biomass energy generation from orchard wastes decreases.

In order to make full use of the plum orchard age and acreage dataset provided by LandIQ, a model was generated in R that accounts for each plum orchard block as a unique entity and applies biomass accumulation processes (based on orchard removal records obtained from G&F Agriservices), probabilistic estimates of age at removal, spatial relationship to biomass power plants, biomass power plant capacity to accept agricultural biomass, and competition from other perennial crop removals to predict the quantity of plum biomass that can be used as a biomass energy feedstock and thus generate GHG reduction credits for fossil fuel offset in any given year (Figs. 5-6). Essentially, this model simulates the Central Valley orchard landscape and walks through each year from 1984 (the first year of available aerial imagery on which the LandIQ dataset is based) through year 2050, accounting for orchard growth and potential changes in biomass energy infrastructure. Out of 100 simulation runs, the mean predicted value for plum orchard removal biomass going to energy production in 2018 was about 84%. This value varies between 80% and 90% through 2025, and between 50% and 100% through 2050. Interestingly, scenario analysis for biomass power plant closure patterns shows that potential plum biomass delivery to energy production is relatively insensitive to changes in power plant availability, except in the worst case scenario where all currently active plants are closed by 2020 (Fig. 7).

Model predictions become more uncertain the farther they are in the future. This uncertainty is driven largely by the models assumption that total plum acreage remains constant – that is, plum orchards are assumed to be replaced with plum orchards upon removal, and no other orchard types are replaced with plums upon removal. This shortcoming will be addressed by incorporating economically modeled grower decision making and allowing changes in total acreage in different perennial crops, based on further geospatial data from LandIQ for plum and other crops. Although this model predicts that energy production is likely to remain a significant option for orchard clearing biomass management, the magnitude of the avoided fossil fuel emissions, or GHG credits to the plum production system, are less significant to net plum production GHG impacts than they are in some other orchard crops. GHG emissions are normally quantified as Global Warming Potential, a measurement which reports emissions of various GHGs as carbon dioxide equivalents, accounting for the varying ability of different gases to trap heat.

This analysis reports GHG emissions as individual gases, GWP_{100} (Global Warming Potential over a 100 year timeframe), GWP20 (Global Warming Potential over a 20 year timeframe), and $TAWP_{100}$ (Time Adjusted Warming Potential). This last measurement also reports GHG impacts as carbon dioxide, but accounts for differences in impact based on the timing of emissions or avoided emissions – allowing quantification of temporary carbon storage on orchard lifespan timescales. For example – one kg of carbon dioxide taken up into orchard tree biomass at orchard establishment results in some 30 years of avoided heat trapping in the atmosphere, whereas the same kg of carbon dioxide trapped just before orchard clearing may result in avoided heat trapping for one year or less. Such temporary storage may provide a more significant GHG credit in plum production than fossil fuel offset from biomass energy generation (Fig. 8) – especially with ongoing decarbonization of California electricity grid.

Incorporation of standing biomass into orchard floor soils upon clearing provides a mechanism by which temporary carbon storage in can be extended past the end of orchard life, thereby increasing climate benefits. Experiments with almond wood have highlighted the carbon storage potential of this practice, as well as that of orchard floor soils in general. Almond results were used to parameterize a plum soil carbon storage model (Fig. 8). These results should be considered preliminary and not necessarily directly applicable to the plum orchard context, but they indicate the need for further investigation of the potential benefits of soil carbon storage.

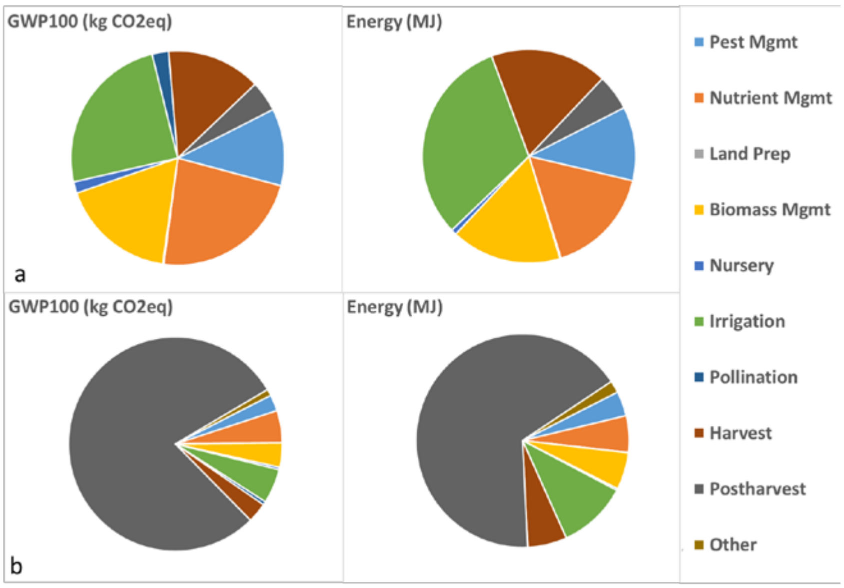

Figure 1. Environmental impacts of major California tree crops as GWP_{100} greenhouse gas emissions (kilograms carbon dioxide equivalent over a 100 year timeframe) and energy use (MJ) per acre. Impacts are labeled by management category and presented as "nursery to orchard gate" (a) and "nursery to postharvest processor gate" (b).

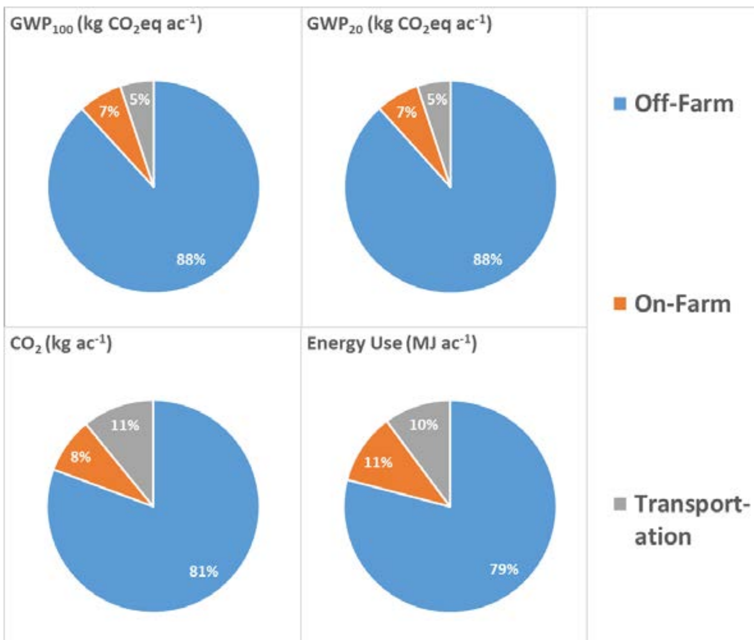

Figure 2. Distribution of selected plum production impacts between life cycle phases.

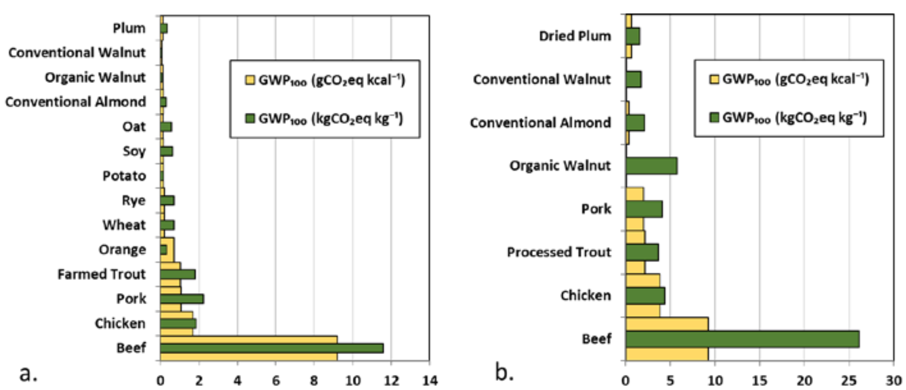

Figure 3. Comparison of environmental impacts of dried plum production as GWP_{100} greenhouse gas emissions (kilograms carbon dioxide equivalent over a 100 year timeframe), per unit yield (kg) and per nutritional calorie (kcal), with other agricultural products. Results are shown for analytic scopes "nursery to farm gate" (a) and "nursery to postharvest gate" (b).

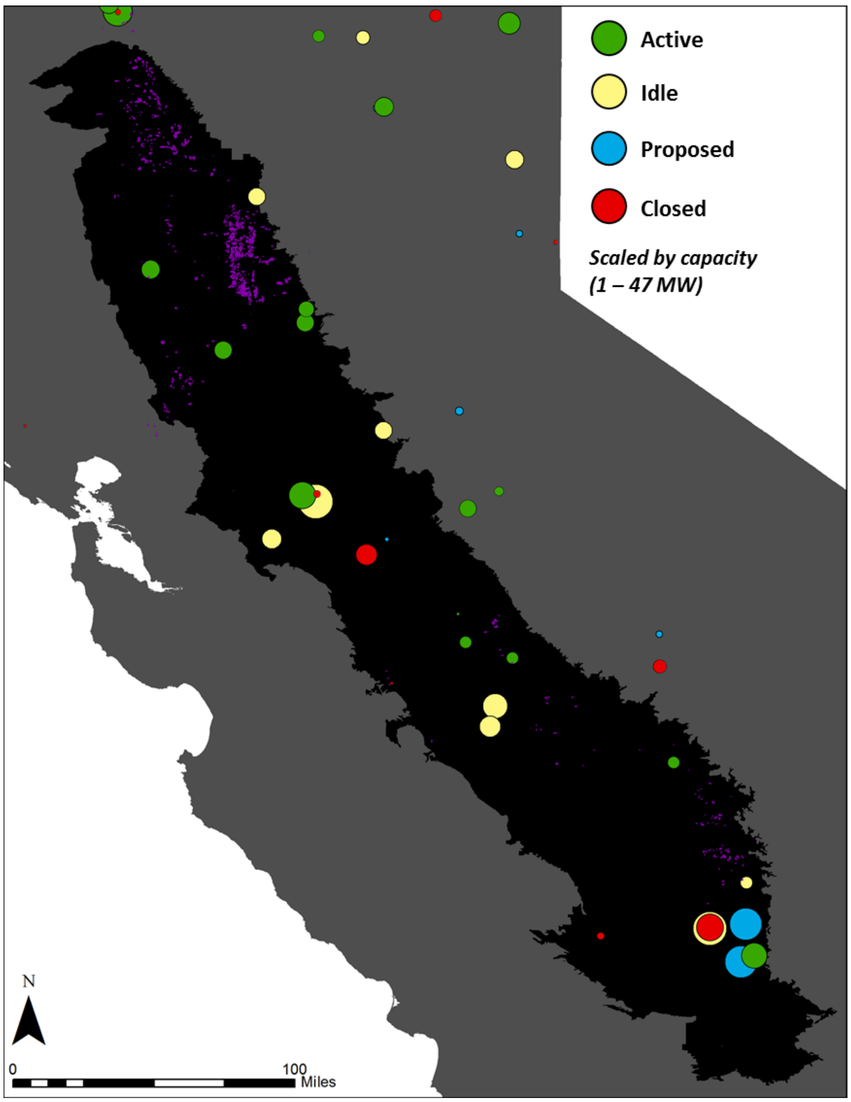

Figure 4. California biomass energy infrastructure and plum orchard distribution, obtained from LandIQ geospatial dataset.

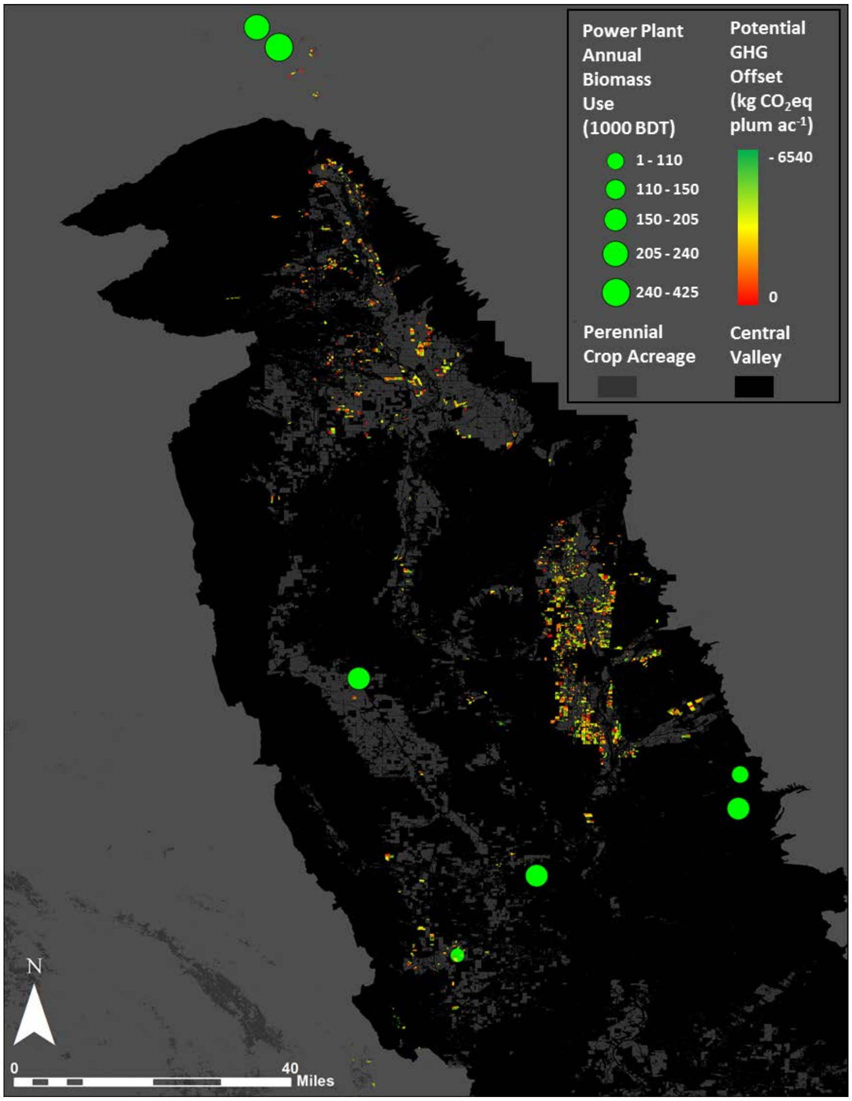

Figure 5. California biomass energy infrastructure as a determinant of the available biomass-to-energy 'sink' for plum orchards in the northern Central Valley as estimated for year 2018. Plum acreage is color coded by potential GHG offset credit derived from orchard clearing biomass delivery to energy production, based on orchard block age, distance to power plants, transport impacts, and power plant ability to accept biomass accounting for competition from other perennial crops.

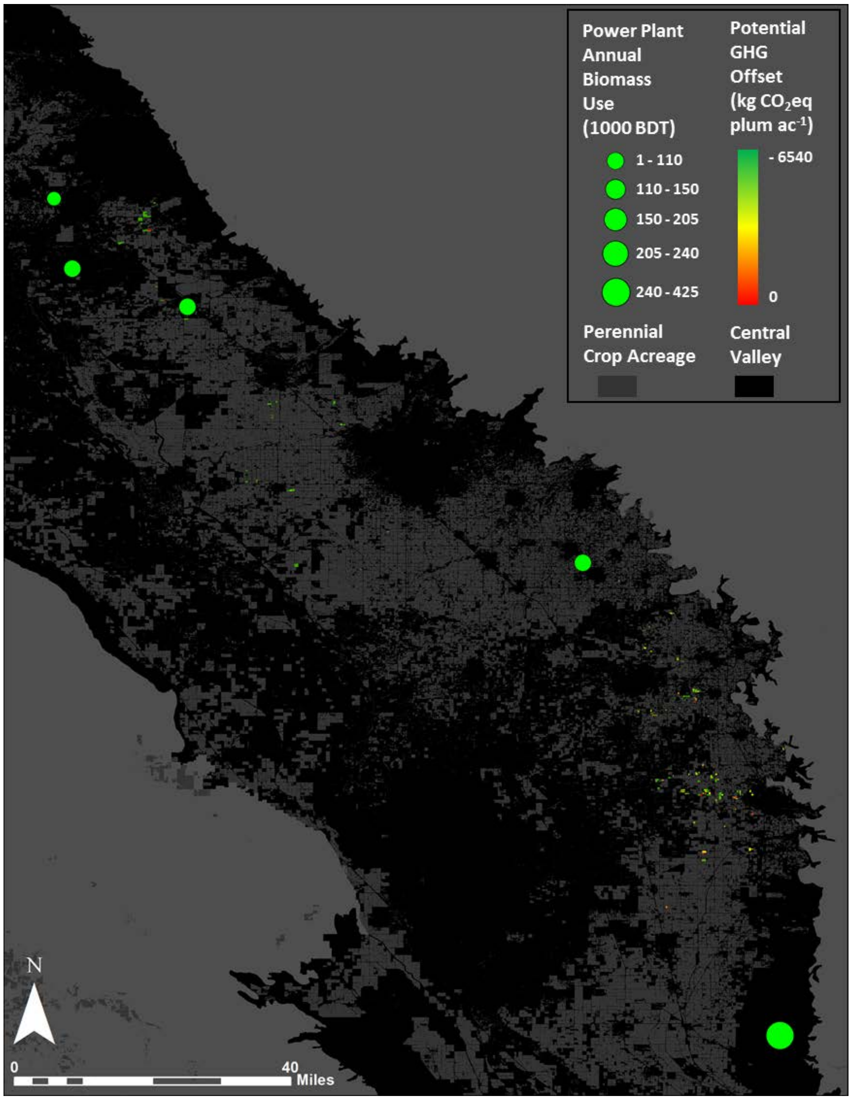

Figure 6. California biomass energy infrastructure as a determinant of the available biomass-to-energy 'sink' for plum orchards in the southern Central Valley as estimated for year 2018. Plum acreage is color coded by potential GHG offset credit derived from orchard clearing biomass delivery to energy production, based on orchard block age, distance to power plants, and power plant ability to accept biomass accounting for competition from other perennial crops.

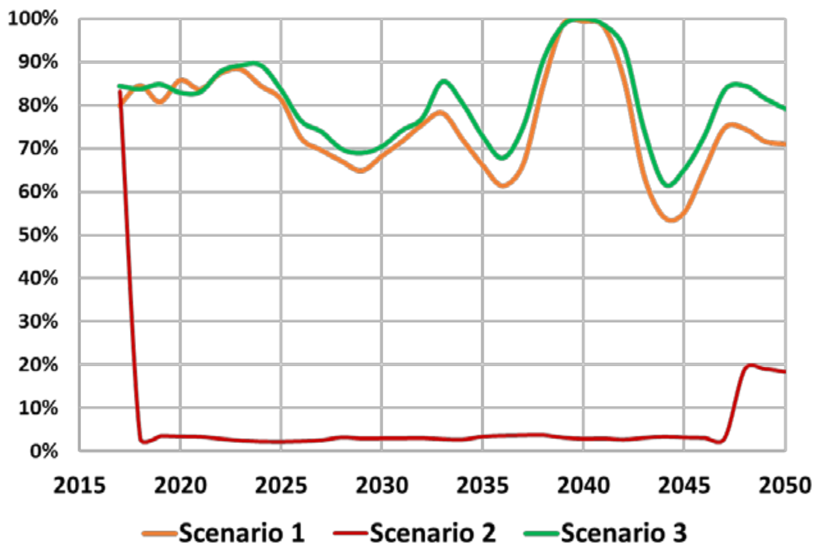

Figure 7. Prediction of plum orchard potential to generate energy feedstock from end of life biomass from year 2017 through 2050, accounting for competition from other perennial crops at end of life and various scenarios for biomass power plant operational status. Scenario 1: currently active power plant status maintained through 2050. Scenario 2: most currently active power plants closed by 2020, only new projects/ proposals active through 2050. Scenario 3: current plants maintained through 2050, plus currently idled BMPPs returned to active status starting in 2020 (2 reactivated every 5 years).

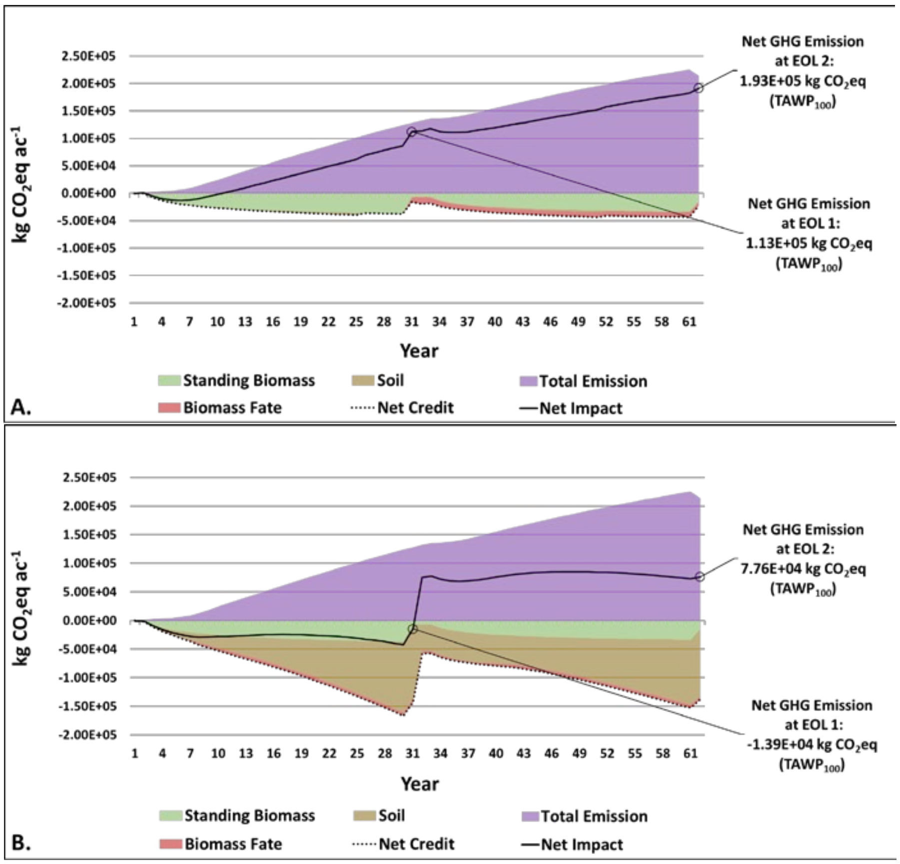

Figure 8. Net greenhouse gas emission estimates from dried plum production over two consecutive orchard life cycles for a generalized orchard block removed in year 2018 and replanted in the following year. Emissions are reported as Time Adjusted Warming Potential over a 100 year analytic timeframe ($TAWP_{100}$), an alternative to the typical Global Warming Potential (GWP). This measurement allows quantification of short term climate benefits from carbon storage in standing biomass and soil. A) Business as usual production and end of life biomass handling practices. B) Maximum benefits from carbon storage in soil as estimated from almond barrel experiment results.

Impact Category	per acre life cycle total	per acre mean annual	per dry kilogram	per nutritional calorie
Carbon dioxide (CO_2) emission (kg)	1.70E+05	5.65E+03	1.85E+00	7.72E-04
20-year Global warming potential (GWP_{20}) (kg CO_2 equivalent)	1.49E+05	4.97E+03	1.63E+00	6.79E-04
100-year Global warming potential (GWP_{100}) (kg CO_2 equivalent)	1.47E+05	4.91E+03	1.61E+00	6.71E-04
Nitrous oxide (N_2O) emission (kg)	2.22E+01	7.39E-01	2.43E-04	1.01E-07
Methane (CH_4) emission (kg)	3.16E+02	1.05E+01	3.46E-03	1.44E-06
Sulfur hexafluoride (SF_6) emission (kg)	1.49E-03	4.98E-05	1.63E-08	6.80E-12
Energy use (MJ)	1.53E+06	5.09E+04	1.67E+01	6.95E-03
Particulate matter 2.5 micron ($PM_{2.5}$) emission (kg)	1.47E+01	4.89E-01	1.60E-04	6.68E-08
Ozone (O_3) emission (kg)	2.25E-01	7.51E-03	2.47E-06	1.03E-09
Lead (Pb) emission (kg)	9.22E-03	3.07E-04	1.01E-07	4.20E-11
Non-methane volatile organic compound (NMVOC) emission (kg)	1.95E+01	6.49E-01	2.13E-04	8.87E-08
Carbon monoxide (CO) emission (kg)	2.66E+02	8.87E+00	2.91E-03	1.21E-06
Nitrogen oxide (NO_x) emission (kg)	2.38E+02	7.95E+00	2.61E-03	1.09E-06
Sulfur dioxide (SO_2) emission (kg)	3.38E+02	1.13E+01	3.69E-03	1.54E-06
Acidification potential (kg H^+ equivalent)	2.67E+04	8.90E+02	2.92E-01	1.22E-04
Eutrophication potential (kg N eq)	1.05E+01	3.52E-01	1.15E-04	4.81E-08
Smog-forming potential (kg O_3 equivalent)	2.88E+03	9.59E+01	3.15E-02	1.31E-05

Table 1. Life cycle inventory of environmental impacts associated with dried plum production reported by various functional units.

Impact Category	Off-Farm	On-Farm	Transportation
Carbon dioxide (CO_2) emission (kg)	5.53E+04	5.80E+03	7.47E+03
20-year Global warming potential (GWP_{20}) (kg CO_2 equivalent)	1.32E+05	9.91E+03	7.53E+03
100-year Global warming potential (GWP_{100}) (kg CO_2 equivalent)	1.30E+05	9.89E+03	7.52E+03
Nitrous oxide (N_2O) emission (kg)	6.63E+00	1.54E+01	1.41E-01
Methane (CH_4) emission (kg)	3.15E+02	5.70E-01	2.93E-01
Sulfur hexafluoride (SF_6) emission (kg)	1.49E-03	0.00E+00	0.00E+00
Energy use (MJ)	6.11E+05	8.32E+04	7.84E+04
Particulate matter 2.5 micron ($PM_{2.5}$) emission (kg)	8.50E+00	3.73E+00	2.44E+00
Ozone (O_3) emission (kg)	2.26E-01	-3.14E-04	0.00E+00
Lead (Pb) emission (kg)	9.22E-03	0.00E+00	0.00E+00
Non-methane volatile organic compound (NMVOC) emission (kg)	4.79E+00	8.82E+00	5.85E+00
Carbon monoxide (CO) emission (kg)	4.35E+01	2.00E+02	2.23E+01
Nitrogen oxide (NO_x) emission (kg)	7.39E+01	5.90E+01	1.05E+02
Sulfur dioxide (SO_2) emission (kg)	1.12E+02	2.25E+02	7.31E-01
Acidification potential (kg H^+ equivalent)	8.64E+03	1.38E+04	4.25E+03
Eutrophication potential (kg N eq)	3.27E+00	2.61E+00	4.66E+00
Smog-forming potential (kg O_3 equivalent)	9.51E+02	1.51E+03	4.18E+02

Table 2. Life cycle inventory of environmental impacts associated with dried plum production reported by life cycle phase over total orchard life cycle.