# General description

The goal of these analyses was to obtain estimates of energy use and greenhouse gas emissions for irrigated alfalfa production in California. Acre-wise, alfalfa is a major agricultural commodity in California, and some amount of production occurs in X of the X counties in California (NASS), but due to the wide variation in soils and climates within California borders, there is equally wide variation in alfalfa production systems. The Department of Agricultural and Resource Economics at University of California periodically releases regional estimates for costs of production for select commodities. These are based on county-based representative management schedules which are determined through iterative discussions between extension employees and producers. Based on availability of these cost-estimates and their attendant management templates, three regions of alfalfa production were chosen as representative systems for this analysis (Figure 1).

|  |
| --- |
| A map of the state of california  Description automatically generated |
| Figure 1 California USA counties with more than 10,000 hectares (dark blue) of irrigated alfalfa production, with Siskiyou, Tulare, and Imperial counties highlighted in red indicating the three county production scenarios used in these analyses. |

# Production data

To drive the calculations, a baseline scenario was constructed for each county. Creation of these baselines centered around the information provided in the enterprise budgets, and were supplemented with interviews and publicly available data (see supplemental material for details).

Parameters were varied from 0.5 to 1.5 times their baseline values. Parameters in which the true value is not known were

|  |  |
| --- | --- |
| Parameters tested to assess uncertainty in results stemming from methodology choices | Parameters tested to assess sensitivity of results to variation in contextual conditions |
| Asssumed fuel requirements for given types of passes  IPCC nitrous oxide calculation assumptions  Conversion factors | Fertilizer credit for subsequent crop  Alfalfa planting rate  Irrigation water source (surface, well)  Amount of irrigation water applied  Efficiency of establishment irrigation system  Efficiency of production irrigation system  Irrigation pump type and energy source  Fertilizer used  Stand life  Number of alfalfa harvests per year  Dry matter harvested per year  Insecticide application  Herbicide application |

In order to explore future scenarios or interventions, we changed parameters to achieve the following scenarios within the three production contexts.

Electric harvesting equipment

Electric tractor for spraying and fertilizer applications

Electric irrigation equipment

Drip irrigation installation

Once the baseline scenarios were run, select additional scenarios were identified and ran (Table 2). It may be more informative to create ‘worst case scenarios’, for example in Tulare where all water requirements are met using the deepest well with the highest pump pressure with the most inefficient irrigation method.

##### Table 2A and B. Scenarios and sensitivity tests– note all changes are individually made to the base scenario (i.e. no stacking of scenarios has been done).

|  |  |  |
| --- | --- | --- |
| Name | Sensitivity | Description |
| ***Sensitivity testing*** | | |
| All ground water | Water source | All water requirements are assumed to be met using water pumped at 25 psi from 150 foot deep well |
| All surface water | All water requirements are assumed to be met using water pumped at 25 psi from a surface source |
| Surface water, gravity fed irrigation (no irrigation energy used) | Irrigation energy | (Tulare only) |
| Stand life extension | Stand life | Stand life is increased by one-third (3 to 4 years in Tulare, 6 to 8 years in Siskiyou) |
| Double pump pressure | Pump pressure | Pump pressure is doubled from 25 psi to 50 psi |
| Double well depth | Well depth | Well depth is doubled from 500 to 1000 feet, larger the range the more impactful this assumption |
| Eliminate insecticides | Use of insecticides | Eliminate passes and products |
| Eliminate herbicides | Use of herbicides | Eliminate passes and products |
| Eliminate pesticides | Pesticide choices | Eliminate passes and embedded energy |
| No leaching-derived N2O emissions | IPCC assumptions | N2O resulting from leached N were included in the baseline scenario, but this may not be applicable in California. Does leaching occur? This scenario showed this assumption (yes or no) has very little impact on the outcomes. |
| Pasture carbon credit | Carbon sequestration estimates | From California Healthy Soils, specific to each county |
| No carbon credit | Carbon sequestration inclusion | From California Healthy Soils, specific to each county |
| Eliminate fertilizer offset | Including this credit | The crop following alfalfa will require less nitrogen compared to if it followed another annual crop. Many studies don’t take this credit into account. |
| ***Scenarios*** | | |
| Deficit irrigation | Understand how deficit irrigation impacts outcomes | (Tulare only)  Water use is decreased from 64 ac-in per year to 51 ac-in per year (based on Ottman and Putnam; <https://alfalfa.ucdavis.edu/+symposium/2017/PDFfiles/Ottman%20Mike.pdf>), no July and August harvests of hay resulting in only 7 harvests instead of 9. Hay yields are reduced from 10 Mg ha-1 per year to 7 Mg ha-1 per year. All other field activities are assumed to remain the same. |
| Electrify irrigation | Understand how impactful such a switch would be | Change energy source for pumping irrigation water to electric (90% work conversion efficiency). |
| Electrify harvest operations | Understand impact of electrifying harvesting activities | Change harvest operations energy source to electric. |
| Electrify field operations | Understand impact of electrifying other field activities | Change all operations except harvest to electric. |
| Change from flood/sprinkler irrigation to drip irrigation | Understand impact of installing drip irrigation | Here we assume you have to apply more water than the crop actually needs due to water losses from the irrigation type. Efficiencies are flood < sprinkler < drip (70%, 80%, 90%). |

The above information was used to calculate energy and GHG emissions using the calculations described below

# Energy and GHG components of alfalfa production

The system boundaries were defined as cradle to farmgate, meaning the transportation of the end product to the point of consumption is not considered in these calculations.

Four functional units of analysis were calculated, with values amortized over the stand life of the alfalfa. This means that, for example, the energy used for planting activities on a per-year basis would be lower for alfalfa with a stand life of 8 years compared to alfalfa with a stand life of 4 years. The four functional units were as follows:

1. Energy used per unit land per year (MJ ha-1 year-1)
2. Energy used per unit of dry matter production per year (MJ Mg-1 year-1)
3. Carbon dioxide equivalents (CO2e) released (positive) or sequestered (negative) per unit land area per year (CO2e ha-1 year-1)
4. CO2e released/sequestered per unit of dry matter produced per year (CO2e Mg-1 year-1)

The contributing components to energy and GHG calculations are summarized in Table X and are described in detail below.

##### Table X. Summary of components contributing to energy and GHG impacts from alfalfa production in California

|  |  |  |
| --- | --- | --- |
| **Impact category** | **Direct** | **Indirect** |
| Energy | Consumption of energy on the farm in the form of fuel used to run tractors and irrigation pumps | Energy used to manufacture products consumed during alfalfa production, including fertilizers, pesticides, and seed. Manufacturing of durable products such as machinery and pumps was not included. |
| Greenhouse gas (GHG) emissions | GHG released from combustion of fuel, CO2 sequestered in the soil and reduction in N2O resulting from a given intervention based on California Healthy Soils models, N2O derived from the application of fertilizers and plant material to the soil | GHG released during the manufacturing of products consumed during alfalfa production, N2O produced from volatilization and leaching of N from the soil, reduction in fertilizer use in subsequent crop due to ‘alfalfa credit’. |

## Energy

### Direct

#### Energy consumed by tractor for field operations

Energy may be consumed on-farm in the form of fuel for field operations (including tractors or airplanes) and movement of water for irrigation. The fuel consumed by a tractor for a given operation is a function of several variables, including the type of fuel used, size of the tractor, soil texture, and the operation being performed. The NRCS developed a database of average diesel fuel usage per unit land area for over 400 (very) specific field operations. This database is used to drive the energy use estimates in Field to Market’s Fieldprint Calculator (<https://calculator.fieldtomarket.org/>), a tool used by consumer packaged goods companies to report their agricultural intervention impacts. For the present analysis, general field pass types were identified, and the median NRCS value within each general category was used (ST1). For example, within the chisel plowing category the NRCS database listed fuel consumptions ranging from 6.9 L ha-1 (e.g., for chisel plowing with a 12-16 inch low crown sweep 3-4 inches deep) up to 17.5 L ha-1, with a median value of 11.7 L ha-1. Chisel plowing represented the highest fuel-consuming tractor category, while surface applications of products (herbicides, fertilizers) represented the lowest fuel-consuming category at 1.2 L ha-1.

##### Supplemental Table S1. Field activity categories and associated fuel usage

|  |  |
| --- | --- |
| **Field operation** | **Diesel use (L ha-1)** |
| Chisel | 11.7 |
| Laser level; inject fertilizer | 8.4 |
| Disk, disk border ridges, stand termination | 7.0 |
| Chop, swatch, stack hay or haylage | 6.8 |
| Plant | 5.1 |
| Spike | 4.1 |
| Bale hay, corrugate | 3.6 |
| Roll | 3.4 |
| Cut haylage; rake hay | 3.3 |
| Aerial pesticide appliciation | 1.5 |
| Pesticide application; surface fertilizer application | 1.2 |

The amount of fuel consumed was converted to the amount of energy consumed using standard energy content assumptions for each fuel (Table X). In order to assess the impact of changing fuel sources on outcomes, the work efficiencies of the various fuels had to be taken into account. For example, diesel engines do not transfer 100% of the fuel energy into mechanical work; the majority of energy is lost as heat resulting in only 30% of the energy contained in the diesel fuel actually being translated into work (although in tractors there are also inefficiencies as the energy powers a PTO, alternator, etc.). This analysis assumed thermal efficiencies only, meaning our estimates represent best-case scenarios for tractors, and are good estimates for irrigation pumps.

##### Table X. Fuel conversions, work transfer efficiencies

|  |  |  |
| --- | --- | --- |
| Fuel type | Energy content(CITE) | Thermal efficiency  (%; amount of energy output per energy content) |
| Diesel | 39.0 MJ L-1 | 30.3 |
| Propane | 26.3 MJ L-1 | 24.7 |
| Natural gas | 34.5 MJ m-3 | 22.2 |
| Gasoline | 34.6 MJ L-1 | 23.6 |
| Electricity | 3.6 MJ/kWh | 90.6 |

#### Energy consumed by pumps for irrigation

Energy is required to lift and pressurize water for irrigation (Eisenhauer et al. 2021). The ideal amount of energy required to move a given amount of water is based on three main variables: (1) the vertical distance from the pump base to the water level (the water level is assumed to be static for our calculations, and does not lower as water is pumped); (2) the pumping pressure; (3) the gross amount of water pumped. When you adjust the units it turns out to just be the pressure plus the distance pumped multipled by the gross volume.

Regarding the gross amount of water pumped, if a crop requires 8 inches of water, the gross amount of water the producer needs to apply will be more than 8 inches, depending on the type of irrigation they are using; general efficiencies were assumed to be 70%, 80%, and 90% for flood, sprinkler, and drip irrigation, respectively (From Table 19 of Hoffman 1990 which you can’t get a digital copy of). The ideal amount of energy is divided by the various inefficiencies involved in pumping, including pump efficiencies and drive efficiencies. In these analyses we did not include these inefficiencies, and only included the thermal efficiencies of a given fuel. This leads our estimates to be a ‘lowest energy consumption’ scenario, wherein the actual amount of energy will be larger depending on the age and type of pump. If an efficiency were to be incorporated, FTM uses an assumption of 75% pump efficiencies, and 90% efficiencies for gear/belt driven motors and 100% efficiencies for electric motors; these could be incorporated into the calculations if it is felt they are needed.

Our estimated energy consumption for a given pumping depth, pressure, and water amount was compared to that produced by the NRCS energy estimator tool (<https://ipat.sc.egov.usda.gov/Default.aspx>), and were found to match.

The required pump PSI will vary based on many factors. Informal interviews with farmers, irrigation sales/maintenance people, and extension agents in Siskiyou, Imperial, and Tulare areas to produce Table X.

##### Table X. Irrigation pump requirements based on region, source water and irrigation method

|  |  |  |  |
| --- | --- | --- | --- |
| Water source | Irrigation type | Required pump PSI | Notes |
| ***Tulare*** |  |  |  |
| Surface | Flood | 0 | In Tulare, it's all gravity fed from canals |
|  | Drip | 30 | Must put pressure on drip for it to emit water, Mike from AgriValley says 20 psi, but Russel at Landmark says 40-50 psi. Russell was kind of shady. |
|  | Sprinkler | 50 | The sprinklers need 35-60 psi to work properly, according to Herarldo in Imperial Valley |
| Ground | Flood | 50 | You use a 50 psi pump to get ground water |
|  | Drip | 80 | You need the ground water pump (50 psi), and most folks pump it into a holding tank, so you need another pump to get it through the filter (whatever psi you assume for drip) |
|  | Sprinkler | 100 | This one depends on where your ground water is being pumped, could do it directly into the sprinkler system but not likely in Tulare? |
| ***Siskiyou*** |  |  |  |
| Surface | Flood | 50 | In Siskiyou, you have to pump it out of the river, could require 70 psi if you are on a hill |
|  | Drip | 80 | You may or may not need two pumps, depending on where your river water is pumped to. Often it goes through a 'coarse' filter, then is pumped again through a finer filter before entering the drip. |
|  | Sprinkler | 50 | Siskiyou contact (Russ Harman) said you'll just be using the one pump to get it out of the river and into the sprinkler system |
|  | Wheel line | 40 | See above |
|  | Pivot | 40 | It was unclear if the pivot needed a pump directly on it, or if the 'river' pump supplied enough pressure |
| Ground | Flood | 50 | Assume same as surface for all, unclear if a holding tank is used |
|  | Drip | 80 |  |
|  | Sprinkler | 50 |  |
|  | Wheel line | 40 |  |
|  | Pivot | 40 |  |
| ***Imperial*** |  |  |  |
| Surface | Flood | 0 |  |
|  | Sprinkler | 50 | Sprinkler is done using a travelling booster pump, which is definitely going to be diesel (50-60 psi). Suction hose -> filter -> booster pump -> filter -> field |
|  | Drip | 30 |  |

# STOPPED

### Indirect

#### Energy consumed to manufacture fuel used by tractor/irrigation pump

XX

#### Energy used to manufacture applied pesticides

Audsley paper

#### Energy used to manufacture applied fertilizer

The energy required to manufacture a particular type of fertilizer was calculated using estimates for the energy used to produce particular elements of fertilizers presented by the GREET model (CITE; STx)). These values match those used in other studies (Matt Ryan’s study).

##### Supplemental table SX. Energy used to manufacture various fertilizer types (ordered from largest energy requirement to lowest) based on the GREET model

|  |  |
| --- | --- |
| Fertilizer | Value (MJ ka-1 product) |
| UAN-32 | 64.51 |
| Nitrogen | 58.04 |
| Ammonia | 37.67 |
| Potassium phosphates k2hpo4 | 31.46 |
| P2O5 | 30.07 |
| Urea | 28.60 |
| Potassium phosphates kh2po4 | 28.48 |
| Diammonium phosphate nh4 2hpo4 | 24.79 |
| Potassium phosphates k2hpo4 3h2o | 24.17 |
| Phosphoric acid per ton of p2o5 product | 22.11 |
| Ammonium nitrate | 19.47 |
| 11-52-0 map | 15.65 P component,  6.38 N component |
|  |  |
| Triple superphosphate ca h2po4 2 | 15.49 |
| Triple superphosphate ca h2po4 2 h2o | 14.43 |
| Ammonium sulfate nh4 2so4 | 10.65 |
| 10-34-0 | 10.23 P component;  5.80 N component |
|  |  |
| Potassium nitrate kno3 | 10.02 |
| Calcium nitrate ca no3 2 | 9.51 |
| Potassium sulfate k2so4 | 9.49 |
| Sodium nitrate na no3 | 8.34 |
| K2O | 8.24 |
| Potash | 8.24 |
| Calcium nitrate ca no3 2 4h2o | 6.81 |
| Ammonium chloride nh4cl | 6.71 |
| Superphosphate ca h2po4 2 2ca so4 | 4.04 |
| Sulfuric acid | 0.60 |
| CaCO3 | 0.13 |

#### Energy used to manufacture planted alfalfa seed

Alfalfa seed production for the California market occurs in the Imperial Valley (Dan said so, I believe). Therefore, we constructed a seed production scenario in Imperial Valley and used the energy required to estimate the amount of energy required per kg of seed produced; this estimate was used as the embedded energy in alfalfa seeds. *NOTE: It was quite small, put the estimate here.*

## GHG Emissions

Using 100-year global warming potentials to translate GHGs into CO2e would translate to an assumption that any carbon sequestered remains in the soil for at least 100 years. For agricultural systems, this assumption is problematic, and shorter timeframes are likely more feasible. Orchard LCAs (e.g. Marvinney et al. 2015) used an alternative method, ‘Time Adjusted Warming Potential’ so they could account for storage of CO2 in trees and in soils, which they assumed to be 25 years. This really only impacts methane emission warming potential (CITE), and since we don’t have a lot of methane emissions in alfalfa production (only through indirect sources), it doesn’t make a difference what timespan we choose, but I included three different timespans anyways because I do think it is ridiculous to claim carbon sequestered in the soil today will still be there 100 years from now.

### Direct

#### CO2 released from combustion of fuel in tractor (none if electric)

Converting from fuel used to CO2 emissions should have two components: the CO2 released from the actual burning of the fuel, and the CO2 released during the manufacturing of the fuel. The following reference includes the amount released from combustion (which I confirmed in the Alfalfa notes R project – the 10.21 kg CO2 is literally just the amount of carbon contained in a gallon of diesel).

https://www.epa.gov/climateleadership/ghg-emission-factors-hub

Table

Description automatically generated

#### CO2 released from combustion of fuel in irrigation pump (none if electric)

Same

#### CO2 sequestered in soil (and accompanying reduction in N2O emissions)

The net amount of carbon sequestered in the soil during alfalfa production was calculated using the COMET-Planner (CITE) driven California Healthy Soils values (<http://comet-planner-cdfahsp.com/>) based on the county and various practices. The base practice considered in these analyses was ‘Conservation Crop Rotation’ (CPS 328; Decrease fallow frequency or add perennial crop to rotations; Basic rotation) and ‘Pasture and Hay Planting’ (CPS 512). The tool presents impacts in units of metric tonnes of CO2e per acre per year, which was converted to kg CO2e per hectare per year. The impacts on CO2 sequestration and N2O soil emissions for the three counties are presented in Table SX.

##### Supplementary Table X. CO2e from sequestered carbon in soil and avoided N2O emissions rounded to the nearest kg

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | CO2 (kg CO2e ha-1 year-1) | | N2O (kg CO2e ha-1 year-1) | |
| County | Conservation Crop Rotation | Pasture and Hay Planting | Conservation Crop Rotation | Pasture and Hay Planting |
| Tulare | 642 | 2125 | 0 | 543 |
| Siskiyou | 519 | 2990 | 25 | 272 |
| Imperial | 642 | 1730 | 0 | 297 |

#### N2O resulting from soil management from soil

Estimates for nitrous oxide (N2O) omissions were calculated using the 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories Volume 4 Agriculture, Forestry and Other Land Use Chapter 11. Direct emissions were calculated using Tier 1 methodology (Equation 11.1) and included components from synthetic fertilizer applied to soil and the amount of N in crop residues returned to soils at the end of the alfalfa stand-life. Equation 11.6 was used to calculate the amount of N from crop residues and forage/pasture renewal, using values derived from Table 11.1A for alfalfa. The values were amortized over the life of the alfalfa crop, as they are only ‘assigned’ at termination of the crop.

The fertilizer requirement in a crop following alfalfa is often lower than general recommendations for that crop. Therefore, the N2O emissions avoided through this fertilization offset was calculated using the above methodology, but the values were assigned a negative value to indicate a reduction in GHG emissions. The avoided fertilizer N2O emissions were amortized over the life of the alfalfa crop. Based on published studies and extension material N reduction in wheat ranged from 45-90 in one study, and from 78-146 kg N ha-1 reductions in another (Putnam and Pettygrove 2015; <https://www.cdfa.ca.gov/is/ffldrs/frep/pdfs/completedprojects/12-0385-SA_Putnam.pdf>); we chose to use 90 kg N ha-1. For tomatoes we chose an assumed reduction of 170 lb N ac-1 (<https://www.alfalfa.org/pdf/USAFRI/Final%20Reports/2018/18Putnam.pdf>).

### Indirect

#### CO2 released during fuel/energy manufacturing

The CO2e released during the manufacturing of a given amount of fuel (L for liquid fuiels, kwh for electricity) were taken from the Environmental Protection Agency (EPA) and the IPCC emissions factor database. Values for each time horizon are presented in Table Sx.

##### Supplementary Table Sx. Greenhouse gas emissions from manufacturing of three fuels using three impact time-horizons

|  |  |  |  |
| --- | --- | --- | --- |
|  | 20 year | 100 year | 500 year |
| Diesel (kg CO2e L-1) | 2.74 | 2.74 | 2.72 |
| Electricity (kg CO2e KWH-1) | 0.24 | 0.24 | 0.24 |
| Gasoline (kg CO2e L-1) | 2.49 | 2.40 | 2.35 |

When the particular fuel used was not known (for example, in pesticide manufacturing), the amount of energy consumed in manufacturing was converted into GHG emissions by assuming a diesel fuel source. A sensitivity analysis showed this assumption did not have a large impact on the outcomes.

#### CO2 released during fertilizer manufacturing

Need to check, used both GREET and energy-based as above, can’t remember which one I wound up actually using…

#### CO2 released during seed production

Energy used was converted into GHG assuming a diesel fuel source.

#### N2O produced from N volatilization and leaching

This was calculated using IPCC Tier 1 methodology (described in Section X) using equations 11.9, 11.10, 11.11, and 11.3. Volatilization calculations depended on the type of fertilizer applied (urea, ammonium-based, nitrate-based, ammonium-nitrate-based), and leaching could use the default value or a halved value specifically for dry climates. A sensitivity analysis was done and showed no significant change resulting from this assumption. In the case of avoided fertilizer application in the subsequent crop, these values were assigned a negative value to indicate a reduction.