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 various 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).

## Life cycle methodology

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.

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 following four general categories contributed to the energy and CO2e components:

1. Fuel consumed in field passes and irrigation (energy, GHG)
2. Manufacturing of consumed products (embedded energy; GHG)
   1. Pesticides
   2. Fertilizer (both applied to alfalfa, and avoided due to the growing of alfalfa)
   3. Alfalfa seed
3. Soil-derived nitrous oxide emissions (GHG)
4. Net soil carbon sequestration and avoided nitrous oxide emissions (GHG)

Each category is explained below.

Table 1. Baseline assumptions for each region, represented by a single county’s enterprise budget

|  |  |  |  |
| --- | --- | --- | --- |
|  | Tulare County | Siskiyou County | Imperial County |
| Subsequent crop, fertilizer credit from alfalfa | Tomatoes, 170 | Wheat, 80 | Wheat, 80 |
| Planting rate | 25 lb/ac | 20 lb/ac | 20 lb/ac |
| Irrigation source, ground/surface water | 50/50 | 50/50 | 0/100 |
| Well depth (note: NRCS says CA state average is 236 feet) | 500 feet (Mike said 300-1,500 feet, gets deeper as you move west, he thought 500 feet might be a good estimate for Tulare) | 150 feet | NA |
| Amount of water applied | 8 ac-in establishment,  64 ac-in/year production | 4.5 ac-in establishment,  24 ac-in/year production | 18 ac-in establishment,  84 ac-in/year production |
| Establishment irrigation type, efficiency | Sprinkler, 80% | Pivot, 80% | Sprinkler, 80% |
| Production irrigation type, efficiency | Flood, 70% | Pivot, 80% | Flood, 70% |
| Role of pump (see pump table) | Before drip (filter and pressure reg), before sprinkler (probably contracted out) regardless of water source | Pump from river or ground for flood, add’l pump for drip (to go through filter and control pressure in lines), one pump for all other application types | Pump into sprinkler or drip system, no pumps for flood irrigation. |
| Irrigation pump energy source, work conversion efficiency | Diesel, 30% | Diesel, 30% | Diesel, 30% |
| Fertility | 200 lb/ac MAP at establishment | 300 lb/ac MAP at establishment, 25 gal 10-34-0 each production year | 200 lb/ac MAP and 250 lb/ac potash at establishment, 75 lb/ac MAP and 250 lb/ac potash each production year |
| Stand life | 3 years | 6 years | 3 years (Irrigation guy didn’t like this number, but it’s the enterprise budget value) |
| Number of harvests | 9 (2 haylage, 7 hay) | 3 | 12 (3 green chop, 9 hay) |
| Dry matter harvested | 8 dry Mg/ha | 3 dry Mg/ha Giuliano says 4.5-7.5, unsure if this dry or not | 8 dry Mg/ha (Ali didn’t like this number, but it is what is in the enterprise budget) |
| Pesticide application method | Tractor | Tractor, could do through irrigation system | Tractor/aerial |
| Average number of field passes per year | 11 | 6.8 | 16 |

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

|  |  |
| --- | --- |
| Name | Description |
| All ground water | 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 |
| Deficit irrigation | (Tulare only)  Water use is decreased from 64 ac-in per year to 51 ac-in per year (based on Ottman and Putnam), 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. |
| Stand life extension | Stand life is increased by one-third (3 to 4 years in Tulare, 6 to 8 years in Siskiyou) |
| Double pump pressure | Pump pressure is doubled from 25 psi to 50 psi |
| Double well depth | Well depth is doubled from 500 to 1000 feet, larger the range the more impactful this assumption |
| Eliminate pesticides | Eliminate passes and embedded energy |
| Electrify irrigation | Change energy source for pumping irrigation water to electric (90% work conversion efficiency). |
| Electrify harvest operations | Change harvest operations energy source to electric. |
| Electrify field operations | Change all operations except harvest to electric. |
| Change from flood/sprinkler irrigation to 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%). |
| Eliminate insecticides | Eliminate passes and products |
| Eliminate herbicides | Eliminate passes and products |
| Surface water, gravity fed irrigation (no irrigation energy used) | (Tulare only) |
| No leaching-derived N2O emissions | N2O from volatilization provides wet and dry climate values (used dry climate values). The fraction leached is set at 0.24 ‘in wet climates’, but the leaching/runoff derived N2O has only a static value (0.011 of the amount leached). May need to rerun everything eliminating this component (I don’t think California has a nitrogen leaching problem?) |
| Pasture carbon credit | From California Healthy Soils, specific to each county |
| No carbon credit | From California Healthy Soils, specific to each county |
| Eliminate fertilizer offset | 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. |

Ottman and Putnam (??) deficit irrigation with alfalfa: What are the economics? <https://alfalfa.ucdavis.edu/+symposium/2017/PDFfiles/Ottman%20Mike.pdf>

IPCC 2019 refinement https://www.ipcc-nggip.iges.or.jp/public/2019rf/vol4.html

# Energy and GHG components of alfalfa production (see separate table)

## 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 1). 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. Diesel engines do not transfer 100% of the fuel energy into mechanical work; the majority of energy is lost as heat (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, and CO2e release

|  |  |  |  |
| --- | --- | --- | --- |
| Fuel type | Energy content(CITE) | Thermal efficiency (%; amount of energy output per energy content) | CO2e released from fuel use |
| 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 |  |

### Indirect

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

Irrigation requires energy to move water.

Need to put calcs in here.

These calculations were compared to those produced by the NRCS energy estimator tool (<https://ipat.sc.egov.usda.gov/Default.aspx>), and were found to match.

#### Energy used to manufacture applied pesticides

#### 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 seed

Seed production can be estimated from the energy required to grow the crop, minus the harvest events.

1. Energy NOT consumed due to alfalfa-derived N credit for next crop

## GHG Emissions

### 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

I don’t know where to get information on the GHG associated with the manufacture of fuels. Answer: GREET

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

#### 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

#### 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.

Pump table

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| county | water\_source | irr\_type | Surface source, pump psi | Ground source, pump psi |
| tulare | surface | flood | 0 | 50 |
|  |  | drip | 30 | 80 |
|  |  | sprinkler | 50 | 100 |
| siskiyou | surface | flood | 50 | 50 |
|  |  | drip | 80 | 80 |
|  |  | sprinkler | 50 | 50 |
|  |  | wheel line | 40 | 40 |
|  |  | pivot | 40 | 40 |
| imperial | surface | flood | 0 | - |
|  |  | sprinkler | 50 | - |
|  |  | drip | 30 | - |

GHG

Using 100-year GWP (to combine gases, as is standard) means any carbon that is sequestered and released within a 100 year timeframe is NOT allowed to be counted. The orchard folks (Marvinney et al. 2015) used an alternative method, ‘Time Adjusted Warming Potential’ so they could account for storage of CO2 in trees. To do this you need an estimate of how long the carbon will remain in the soil (they said 25 years). This really only impacts methane emission warming potential, and since we don’t have a lot of methane emissions in alfalfa production, it doesn’t make a difference what timespan we choose.

# Variability:

The categories Steinmann et al. 2014 report are spatial, temporal, and technological. There could be others. These are things under our control, and that present opportunities for optimization. Temporal is hard, and isn’t used in their example.

Spatial (3): Intermountain, central valley, imperial valley

Technological (5):

1. Irrigation source (ground vs surface)
2. Irrigation efficiency (flood, drip, etc.)
3. Fuel source for irrigation (diesel vs electric)
4. Fuel source for harvesting activities (diesel vs electric)
5. Fuel source for field activities (diesel vs electric)
6. Deficit irrigation – normal irrigation until a point, then just stop. Impacts number of harvests and irrigation
7. Low input vs high input?
8. Stand life?

Political (3):

1. No carbon credit
2. Incorporating perennial credit
3. Transitioning to permanent perennial credit

# Uncertainty:

Uncertainty results from 1) lack of knowledge of true value, 2) an arbitrary choice, 3) simplification of reality. Need to think about distribution curves most appropriate for each parameter. For parameters varying from 0-infinity, a log-normal distribution could be used. For positive values with finite ranges, a pert-distribution might be good.

Are these correlated? If not you can do a one-at-a-time sensitivity analysis using the min and max values to see how big of a perturbation they cause.

1. Amount of system N leaving as N2O emissions (0-?% use literature to define a max?)
2. Fuel/energy required for field passes (Could we set a reasonable minimum/maximum?)
3. Depth of well to ground water?(0-?)
4. Data source for energy content of fuels (3 options)
5. Whether you include fuel thermal efficiencies (2 options)
6. Yields (they vary by year, normal distribution?)
7. Time horizon for GWP (20 or 100 year, 2 options)

# Notes:

Lots of warnings about picking one impact category and calling it an LCA

A need to distinguish between uncertainty and variability

Energy is first step, GHG is built upon that calculation

# Components of alfalfa production needing GHG estimates

## Energy

Direct

1. Energy consumed by tractor for field operations
   1. Energy requirement is based on physics
   2. Energy actually used depends on fuel and how efficiently it transforms energy into work
      1. Diesel transforms 30% of it’s energy release into work
      2. Electricity transforms 90%
      3. FTM ignores these inefficiencies, NRCS tool does not
2. Energy consumed by pump for irrigation, depends on fuel used

Indirect

1. Energy consumed to manufacture fuel used by tractor/irrigation pump
   1. Fossil fuels require less energy to produce compared to electricity
      1. This is because often electricity is produced by burning fossil fuels
      2. Could find generation-specific values (a hydropower plant, a coal-fired plant)
      3. Currently estimates are based on a region’s electricity source profile
2. Energy used to manufacture applied pesticides
3. Energy used to manufacture applied fertilizer
   1. I think there must be a better source for this, GREET has a value for N, PO5, etc. and you just add those values up. So UAN-32 and ammonia have the same embedded N energy value
4. Energy used to manufacture planted seed

## GHG Emissions

Direct

1. CO2 released from combustion of fuel in tractor (none if electric)
2. CO2 released from combustion of fuel in irrigation pump (none if electric)
3. CO2 sequestered in soil
4. N2O formed and released from soil

Indirect

1. CO2 released during fuel/energy manufacturing
2. CO2 released during pesticide manufacturing
3. CO2 released during fertilizer manufacturing
4. CO2 released during seed production
5. N2O produced from downstream soil N leaching
6. N2O NOT produced due to reduced fertilizer needs of next crop

**Tulare back-of-envelope example**

|  |  |  |
| --- | --- | --- |
|  | **Flow** | **kg co2e per ha per year** |
| 1 | Fuel combustion for field operations | 1,000 |
| 2 | Fuel manufacturing | 1,000 |
| 3 | Insecticide/herbicide manufacturing | 100 |
| 4 | Seed production | 10 |
| 5 | Fertilizer manufacturing | 200 |
| 6 | Irrigation energy | 2,000 |
| 7 | Nitrous oxide emissions | 200 |
| 8 | Avoided emissions from reduced fertilizer in next crop | 200 |
| 9 | Carbon sequestered | 500 |