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:

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)
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
2. Manufacturing of consumed products
   1. Pesticides
   2. Fertilizer
   3. Alfalfa seed
3. Soil-derived nitrous oxide emissions
4. Net soil carbon sequestration

Calculations and assumptions are described in detail below.

### Fuel consumed in field passes and irrigation

Energy may be consumed on-farm for field operations (including tractors or airplanes) and movement of water for irrigation.

#### Field passes

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, 25 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 (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 consumption tractor category, while surface applications of products (herbicides, fertilizers) represented the lowest fuel consumption category at 1.2 L ha-1. The Imperial Valley cost-estimate study included air application of pesticides, and the NRCS database estimated fuel usage for aerial spraying at 1.5 L diesel ha-1.

#### Irrigation

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.

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 | 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 |  |

### Manufacturing of consumed products

#### Fuel

From a paper, it said ethanol’s carbon intensity is 50 gco2e per MJ ethanol. Conversions (45 MJ/kg ethanol) comes out to 6.6 kg co2e/gal. The paper says this is 40% lower than other fuels. So let’s say 10 kg co2e/gal. This is roughly equivalent to the amount released upon combustion. GREET has more precise values, but this is a good back of the envelope number to compare the GREET values to.

#### Pesticides

Audsley paper.

#### Fertilizer

From the FTM Table 2 (which I’m unsure how it was created, seems to be loosely taken from the Greet ag-chemicals info. Not sure how they converted BTUs to CO2e).

For MAP, they list 6,521 BTUs/lb product. In Tulare they applied 200 lbs per ac, so 1,304,200 btus/ac, or roughly 20 gallons of diesel used per hectare. FTM says ther are 22.7 lbs of co2 eq in a gal of diesel (again, only combustion?), so ~200 kg co2e/ha.

#### Alfalfa seed

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

### Soil-derived nitrous oxide (N2O) emissions

Using IPCC dry-area estimates, the range in CO2eq from N2O emissions avoided per kg N applied is 0-0.005 Mg CO2eq/kgN. The kg N is supposed to include the N applied as fertilizer, the N contained in above ground biomass left in the field, and the N contained in below-ground biomass.

The Tulare example applied 200 lbs of 11-52-0, meaning there was 22 pounds of N applied per acre, roughly 22 kg/ha. This equates to 110 kg co2e/ha from the fertilizer.

A paper from Serbia estimated there was 150 kg root N per ha in an alfalfa field (Vasileva et al. 2015). Not the best source, but fine for estimating. It seems a bit high? They say there is 3 Mg of root material, which would mean the roots are 5% nitrogen.

Another method, if you are adding 500 kg of co2 (see carbon sequestered), that is 130 kg of C. If soil has a C:N ratio of 10, that would mean you are adding 13 kg of N per year to the soil. So root N could be anywhere from 10 to 100 kg N per ha per year. So anywhere from 50-500 kg co2e/ha.

IPCC has direct and indirect emissions. Additionally, you could account for the reduced fertilizer manufacturing emissions.

Direct

Using IPCC dry-area estimates, the range in CO2eq from N2O emissions avoided per kg N applied is 0-0.005 Mg CO2eq/kgN avoided.

Indirect

Need to investigate. Not sure how big of a problem nitrate leaching is in dry areas?

Manufacturing

See fertilizer manufacture for details on that component. Assuming the farmer uses the most GHG-intensive N source of ammonium nitrate, for every kg N avoided they would get a credit of 0.007 Mg CO2eq/kgN.

Best case scenario: 0.012 Mg CO2eq avoided per kg N not applied. About 10 kg?

Wheat following alfalfa obtained 114, 82, and 119 lb N/ac at Davis, Kearney, and Tulelake, respectively (Putnam and Pettygrove 2015) Final report fertilizer research and education program. https://www.cdfa.ca.gov/is/ffldrs/frep/pdfs/completedprojects/12-0385-SA\_Putnam.pdf

### Net soil carbon sequestration

Using the ‘Healthy Soils’ estimates in Tulare county for adding a perennial crop to a basic rotation, they estimate 26 metric tons (Mg?) of co2e will be sequestered per 100 acres of implementation.

26000 kg co2 per 100 acres = 260 kg co2 per acre is roughly 500 kg co2e per ha per year.

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

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

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 its 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) for scenario analysis (what if electricity all came from solar?)
      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. Everyone seems to use this.
4. Energy used to manufacture planted seed
5. Energy NOT consumed due to alfalfa-derived N credit for next crop

## 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

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

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**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 |