# Supplementary material for MANUSCRIPT

## Impact quantification

Irrigation efficiency was used to estimate the amount of water that needed to be put through the irrigation system in order to satisfy the water requirements for the crop. For example, pivot irrigation systems were assumed to delivery water with an efficiency of 80%, so if the crop requires 30 mm of water 37.5 mm were pumped through the irrigation system.

### Direct energy consumption

Energy may be consumed on-farm in the form of fuel for field operations (including tractors or airplanes) and movement of water for irrigation. Each is described in detail below.

#### Energy consumed for performing field operations

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 specific field operations (CITE WEPPS model). For the present analysis, field passes falling within the 11 categories of field operations listed in the enterprise budgets were identified, and the median NRCS value within each category was used (Table S1). For example, within the *chisel* category, the NRCS database lists 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 (for a XX), 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.

##### Table S1. Field activity categories and assumed diesel fuel usage listed in order of descending 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 S2). In order to assess the impact of changing fuel sources used for field operations, the work conversion efficiencies (the amount of energy produced per unit of energy expended) of different fuels were used (CITE).

##### Table S2. Energy contents of fuel and work conversion 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 |

For example, diesel engines do not transfer 100% of the diesel fuel energy into mechanical work. The majority of energy is lost as heat – this results in only 30% of the energy contained in the diesel fuel actually being translated into work. In tractors there are additional inefficiencies as the engine transfers energy through other intermediaries such as PTOs, alternators, etc. The present analysis accounted for thermal efficiencies only, meaning our estimates represent best-case scenarios for tractors, but are good estimates for irrigation pumps.

#### Energy consumed by pumps for irrigation

Energy is required to lift and pressurize water for irrigation (CITE 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. These calculations reduce to a simple equation:

Energy = (pressure) + (distance) x (water volume)

##### Pressure

The pressure required for an irrigation pump will vary based on many factors. Informal interviews with farmers, irrigation sales/maintenance people, and extension agents in Siskiyou, Imperial, and Tulare areas were done to establish good baseline assumptions (Table S3).

##### Table S3. Irrigation pump requirements assumed based on region, source water and irrigation method

|  |  |  |  |
| --- | --- | --- | --- |
| Water source | Irrigation type | Required pump pressure (PSI) | Notes |
| ***Northern CA (Siskiyou County)*** | | | |
| 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 | NA |
|  | Sprinkler | 50 | NA |
|  | Wheel line | 40 | NA |
|  | Pivot | 40 | NA |
| ***Central CA (Tulare County)*** | | | |
| 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? |
| ***Southern CA (Imperial County)*** | | | |
| Surface | Flood | 0 | NA |
| 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 | NA |

##### Distance

The vertical distance the water is pumped is a function of the depth of the well. The well depth assumed in this study was derived from county-level estimates provided by the NRCS energy estimator tool (<https://ipat.sc.egov.usda.gov/Default.aspx>).

##### Water volume

The gross amount of water pumped is a function of the irrigation system’s efficiency, or the unit of water delivered to the crop per unit of water put through the irrigation system. 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 (CITE Table 19 of Hoffman 1990).

There may be a number of other inefficiencies involved in delivery of irrigation water (pump efficiencies, drive efficiencies, etc.) but due to the heterogeneity in irrigation infrastructure, these were not considered in this study, meaning our estimates represent a ‘lowest energy consumption’ scenario, wherein the actual amount of energy will be larger depending on the age and type of pump. Commonly assumed efficiencies are generic 75% pump efficiencies, 90% efficiencies for gear/belt driven motors and 100% efficiencies for electric motors. We compared our calculated values to the NRCS energy estimator tool (<https://ipat.sc.egov.usda.gov/Default.aspx>) and found they matched (for a given pumping depth, pumping pressure, and water amount), providing confidence our values are representative of estimates provided by other entities.

### Indirect energy consumption

Energy is indirectly consumed in multiple ways during the lifecycle of an alfalfa stand. Energy is consumed during the manufacturing of the fuel used for field operations and irrigation delivery, which was estimated as XXXXXX NEED TO LOOK IN THE R CODE. The energy consumed during the manufacturing of pesticides was taken from Audsley et al. xx (CITE). The energy required to manufacture a particular type of fertilizer was calculated using estimates for the energy used to produce particular elements of fertilizers reported by the United States (US) Department of Energy (DOE) Greenhouse gases, Regulated Emissions, and Energy use in Technologies (GREET®) model version CA-GREET4.0 (CITE). We cross-checked our calculations with other studies (Matt Ryan’s study, Grassini) and are presented in Table S3.

##### Table S3. Energy used to manufacture various fertilizer types (ordered from largest energy requirement to lowest) based on the US DOE 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 |

Alfalfa seed production for the California market occurs in the Imperial Valley (Dan said so, CITE). 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 (PUT ESTIMATE HERE).

## GHG Emissions

Greenhouse gas emissions result from energy consumption (often in the form of fuel), which have both direct and indirect emissions. The carbon released as CO2 from the actual burning of the fuel is a direct emission, while the GHG released during the manufacturing of the fuel indirectly contribute to GHG emissions. In agricultural systems, carbon may be directly sequestered into the soil. Additionally, nitrous oxide emissions can be a direct result of field management, including application of nitrogen fertilizers. When growing legumes such as alfalfa as part of a crop rotation, they may also indirectly reduce nitrous oxide emissions

Using 100-year global warming potentials to translate GHGs into CO2e would translate to an assumed carbon sequestration time period of at least 100 years. For agricultural systems, this assumption is problematic, and shorter timeframes are likely more feasible. When accounting for carbon storage, orchard LCAs (e.g. Marvinney et al. 2015) use ‘Time Adjusted Warming Potential’ timespans of 25 years to account for storage of CO2 in trees and in soils, which can realistically be 25 years. This assumption has a larger impact on the conversion of methane into CO2-equivalents, so it has a negligible impact on alfalfa production. However, this analysis uses a 25 year global-warming-potential (GWP) because it is ridiculous to claim carbon sequestered in the soil today will still be there 100 years from now.

### Direct GHG emissions/seqeuestration

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

The actual burning of the fuel releases CO2 based on the stoichiometric amount of carbon contained in a given unit of fuel (Table S4). No CO2 is directly released when the fuel source is electric.

##### Table S4. Carbon released from carbon-based fuel combustion (https://www.epa.gov/climateleadership/ghg-emission-factors-hub)

|  |  |  |
| --- | --- | --- |
| **Fuel type** | **Kg CO2 per unit** | **Unit** |
| Diesel | 10.21 | Gallon |
| Propane | ? |  |
| Natural gas | 0.05444 | Scf |
| Gasoline | 8.78 | Gallon |

The US Environmental Protection Agency (EPA) provides estimates on the amount of carbon released

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).

#### 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 GHG emissions

#### 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.

## Uncertainty and sensitivity analyses

##### Table SX. Uncertainty and sensitivity tests, all changes were made one-at-a-time to the base scenario (i.e. interactions between changes were not assessed).

|  |  |  |
| --- | --- | --- |
| Name | Sensitivity | Description |
| ***Uncertainty testing*** | | |
| Fuel requirements | Assumed fuel requirements | NRCS reports a range of values for tractor operations that are based on soil textures, implements, and tractor specifications. For the baseline scenario the median value was used, but for the sensitivity testing the minimum and maximum values were tested. This test showed XX. |
| 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 test showed this assumption (yes or no) has very little impact on the outcomes. |
|  |  |  |
|  |  |  |
| ***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 |
|  |  |  |
|  |  |  |
|  |  |  |
| 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. |
|  |  |  |
| Pasture carbon credit | Carbon sequestration estimates | For the baseline assumption the Conservation Rotation Credit (NEED TO CHECK TERMINOLOGY) was used, but the pasture establishment credit may be applicable in some situations (large credit), and some situations may warrant no credit. This test showed the assumed carbon credit value from the California Healthy Soils program had a large impact on the outcomes. |

## Scenario exploration

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.

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

|  |  |  |
| --- | --- | --- |
| ***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%). |