Title: Cattle Grazing Reduces Greenhouse Gas and Particulate Matter Emissions from California Grassland Wildfires

Supplemental Appendix

This supplemental appendix offers more detail on the model parameters and equations used to estimate greenhouse gas and particulate matter emissions from livestock management and wildfires. The model works by estimating the amount of CO_2 removed from the atmosphere to create the aboveground biomass in a grassland in a given year (based on the carbon content of the vegetation and the total production of aboveground biomass). The fate of that carbon (and other elements in the aboveground biomass) is then modeled using established emissions factors for livestock, including enteric methane, nitrogen excretion and volatilization, and methane emissions from manure. CO2 from livestock respiration and manure decomposition is calculated after removing the carbon fraction from the total carbon consumed. Emissions from vegetation burned in wildfires are calculated using the emissions factors from Urbanski et al. (2014) and FOFEM (2020). The model tracks all carbon flowing into and out of the system (in aboveground biomass) over the course of a year. Unconsumed biomass is subject to summer decomposition during the summer months and winter decomposition during the winter months, each resulting in CO2 emissions. Belowground carbon balance is not accounted for in this model because the relationship between belowground carbon sequestration and grazing is not well established in California and is likely highly site-specific (Buckley-Biggs and Huntsinger 2021; Booker et al. 2013).

Model steps:

The following model parameters are selected before running the model:

1) Total standing biomass (dry weight) for the area of interest. For the state-wide case study, this was equal to the GIS-based estimate of forage consumed by livestock in burned areas of the state.
2) Mass (dry weight) of forage consumed by cattle.
3) Percent of herbaceous fuel burned by wildfire.
4) Wildfire burn date.

The model then performs the following calculations:

1) Atmospheric CO_2 fixed through photosynthesis in the creation of this biomass is estimated based on the carbon content of herbaceous grassland biomass.
2) IN THE SCENARIOS WITH GRAZING:
    a. Nutrient characteristics of this forage are estimated*.
    b. Total nitrogen excreted in manure is estimated based on the total number of cattle grazing days, and direct emissions of N_2O are estimated based on the fraction of N that is volatilized* and an N_2O emission factor*.
    c. Enteric methane emissions are estimated based on the quantity of forage consumed, forage quality*, and a methane conversion factor*.
    d. Methane from manure is estimated by calculating the volatile solids excreted in manure and multiplying them by an emissions factor.
3) The total amount of forage that is not consumed by livestock grazing is calculated.

4) The fraction of remaining biomass lost to summer decomposition is estimated based on the time elapsed between peak standing crop and a wildfire date or break of season.
5) IN THE SCENARIOS WITH FIRE:
    a. Fuel load is calculated as total standing crop minus the quantity of forage consumed, minus fractional loss due to summer decomposition.
    b. Emissions of CH_4, CO_2, CO, and PM2.5 are estimated based on the percentage of fuel that burns and the emissions factors for each variable*.
6) Any standing biomass left at the end of the year is assumed to decompose over the winter and emissions of CO_2 are calculated based on the carbon content of that biomass.
7) All sinks and emissions from this equation are calculated 1000 times. Each calculation includes random draws from known distributions of key variables. The resulting quantities of GHGs are multiplied by their GWP100 value to produce CO_2e estimates. The black carbon GWP100 value is randomly drawn from a probability distribution (a uniform distribution with a minimum of 100 and a maximum of 1700) because uncertainty is large for this parameter (Myhre et al. 2013).
8) A data frame is populated with the resulting CO_2e values and PM2.5 values from the model and summary statistics are used to create mean values and 95% confidence intervals of the mean from the simulated data.
9) To evaluate the difference in emissions in burned grasslands grazed (and ungrazed) by livestock, the model is run using a grazed and burned scenario and an ungrazed and burned scenario and the results are compared.

* Variables estimated with uncertainty

Supplemental Table 1 outlines the variables used in the model, the default parameters used for estimation, and the range of values and distribution used for the Monte Carlo simulations. Sources are given for model parameters, and full references to those sources are provided below.

Supplemental Equations 1-5 describe how the variables were used to predict greenhouse gas and particulate matter emissions in the model.

Supplemental Table S1. Emission factors and model parameters used in the GHG_PM Model.

Type of factor	Factor	Definition	Source	Units	Default Value	Range	Model distribution
Forage Quality	DE:GE	Digestible energy to gross energy ratio	NRC 2000	Ratio	0.61	0.599, 0.619	Uniform
	Forage TDN	Total Digestible Nutrients	Larsen et al. 2021	%	66.3	54, 74	Uniform
	forage.ash.pct	Percentage of ash in forage	Cromer 2017	%	8.5	8.44, 13.05	Uniform
Livestock Emissions	N2O.direct.EF	Direct emission factor for N2O from manure	IPCC 2019	Proportion	0.002	0.0, 0.006	Uniform

	Ym	CH4 conversion factor—% GE in feed converted to methane	IPCC 2019	%	0.07	0.0686 - 0.0714	Uniform
	UE	Urinary energy—% GE converted to urine	IPCC 2019	%	0.04	None	NA
	Nex.manure	Daily nitrogen excreted in manure	IPCC 2019	kg	0.182	None	NA
	CH4.manure.EF	Emission factor for CH4 from manure. See equation 4a	IPCC 2019	kg	0.006	None	NA
	EF.N2O.volatilization	Emission factor for N2O volatilizing from manure	IPCC 2019	kg	0.005	0, 0.11	Uniform
	FRACgasm	Fraction of N in manure that is volatilized	IPCC 2019	Proportion	0.21	0, 0.31	Uniform
Fire Emissions	EF.Fire.CO	Emission factor for carbon monoxide from grass fires	FOFEM 2020, Urbanski 2014	g	61	SD=21	Normal
	EF.Fire.CO2	Emission factor for carbon dioxide from grass fires	FOFEM 2020, Urbanski 2014	g	1705	SD=44	Normal
	EF.Fire.CH4	Emission factor for methane from grass fires	FOFEM 2020, Urbanski 2014	g	1.95	SD=1.05	Normal
	EF.Fire.$PM_{2.5}$	Emission factor for $PM_{2.5}$ from grass fires	FOFEM 2020, Urbanski 2014	g	8.51	SD=5.12	Normal
Other Parameters	summer.decomp.rate	The monthly rate of the disappearance of aboveground biomass during dry months	Larsen et al. 2021	Proportion	0.082	0.068, 0.096	Uniform

	winter.decomp.pct	The proportion of residual forage that is decomposed over the subsequent winter	No Source	Percent	100	None	NA
	break.of.season	The month when germinating rains initiate forage growth	No Source	Month	Octobe r	None	NA
	standing.crop.C.pct	Percentage of the dry weight of forage that is carbon	Friedl et al. 2005	Percent	45%	None	NA

Supplemental Equations.

Supplemental Equation S1. Atmospheric CO_2 fixed in aboveground herbaceous biomass (e.g., standing crop). The constant 44/12 represents the ratio of the molecular weight of CO_2 to the atomic weight of C incorporated in plant biomass.

$$CO2.fixed(kg) = standing.crop\ (kg) * \left(\frac{standing.crop.C.pct}{100}\right) * \left(\frac{44}{12}\right)$$

Supplemental Equation S2 (a-c). Nitrous oxide emissions from cattle manure. In equations b and c, the constant 1.57 represents the atomic weight ratio of N_2O to N_2. Direct and indirect N_2O emissions are based on the IPCC (2019) Tier 1 approach.

a. $cattle.feces.N\ (kg) = days\ of\ cattle\ grazing\ * \frac{Nex.manure}{day}$

b. $manure.N2O.direct\ emissions\ (kg) = N2O.direct.EF\ *\ cattle.feces.N\ *\ 1.57$

c. $manure.N2O.indirect\ emissions\ (kg) = cattle.feces.N\ *\ FRACgasm\ *$

$EF.N2O.volatilization\ *\ 1.57$

Supplemental Equation S3 (a-c). Methane emissions from enteric fermentation are based on the IPCC (2019) Tier 2 approach. In equation 4c, the constant 4.184 converts from megacalories (MCal) to megajoules (MJ), and 55.65 is the energy content of CH_4.

a. $total.DE.forage\ (MJ) = forage.consumed(kg) * \frac{forage.TDN.pct}{100} * 4.4$

b. $toal.GE.forage\ (MJ) = total.DE.forage * \left(\frac{1}{DEtoGE.ratio}\right)$

c. $enteric.CH4\ (kg) = \frac{(toal.GE.forage * 4.184 * Ym)}{55.65}$

Supplemental Equation S4 (a-c). Methane emissions from manure. Estimation of CH_4 from manure follows the IPCC (2019) Tier 2 approach. IPCC (2019) recommends using a B_0 value of 0.19 for manure deposited on rangelands and an MCF value of 4.7% for pastures and ranges (Table 10.17 in IPCC 2019).

a. $\text{CH4.manure.EF}_{\text{kg per kg volatile solids}} = B_0 * 0.67 * \text{MCF} = 0.0006$ {where $B_0 = 0.19$ and $\text{MCF} = 0.047$}

b. $cattle.volatile.solids.excretion\ (kg) = (toal.GE.forage * (1 - DEtoGE.ratio) + UE * toal.GE.forage) * \left(\frac{1-\frac{forage.ash.pct}{100}}{18.45}\right)$

c. $manure.CH4\ (kg) = CH4.manure.EF\ (\frac{kg\ CH4}{kg\ Volatile\ Solids}) * cattle.volatile.solids.excretion\ (kg)$

Supplemental Equation S5. Emissions from fire. Four emissions (CO_2, CO, CH_4, and $PM_{2.5}$) were separately estimated using the following equation. Emission factors are from FOFEM

(2016) and Urbanski (2014) for grassland wildfire emissions. For emission factors, see Supplemental Table 1.

$$Pollutant\ Emission\ (kg) = \frac{Emissions\ Factor\ (\frac{g}{kg})\ *\ fuel.load\ (kg) * \frac{burn\%}{100}}{1000\ (\frac{g}{kg})}$$

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