Emission Inventory Methodology
Soil Nitrogen Oxides
(March 16, 2022)

EMISSION INVENTORY SOURCE CATEGORY

Biogenic Sources/Soil Nitrogen Oxide

EMISSION INVENTORY CODES (CES CODES) AND DESCRIPTION

EIC	DESCRIPTION
91092120030000	BIOGENIC SOURCES - SOIL - CROPLAND – NO_X
91092220030000	BIOGENIC SOURCES - SOIL - URBAN LAND – NO_X
91092320030000	BIOGENIC SOURCES - SOIL - GRASSLAND – NO_X
91092420030000	BIOGENIC SOURCES - SOIL - SHRUB LAND – NO_X
91092520030000	BIOGENIC SOURCES - SOIL - FOREST – NO_X
91092620030000	BIOGENIC SOURCES - SOIL - FALLOW – NO_X

OVERVIEW

Nitrogen oxides (NO_X) are reactive nitrogen (N) gases that contribute to ozone and particular matter formation in the atmosphere. Soil can emit NO_X through biogeochemical processes driven by soil microorganisms that can convert N compounds into various N gases. However, fluxes of soil N gases are highly variable, both spatially and temporally, depending on local environmental factors that govern soil microbial activities.

This document describes the methodology used by CARB staff to develop inventories of soil NO_X for the California Emissions Inventory Data Analysis and Reporting System (CEIDARS) and the California Emissions Projection Analysis Model (CEPAM). Staff estimated soil NO_X emissions from California lands using a process-based biogeochemical model DeNitrification-DeComposition (DNDC), coupled with California-specific biophysical and cropland management data. The document provides detailed information on the DNDC model, model configuration, data sources, input parameter values, emission estimates and uncertainties. The methodology has been published in several peer-reviewed articles in leading geoscience journals (Guo et al., 2020; Deng et al., 2018a; 2018b) and has been adopted by CARB in developing the State's soil nitrous oxide (N_2O) inventory and soil carbon stock inventory from cropland and methane (CH_4) inventory from rice cultivation since 2017. We also completed the development of CEIDARS and CEPAM inventories for soil ammonia (NH_3) emissions from California lands using the same methodology described in this document. A separate documentation for soil NH_3 is thus not provided.

METHODOLOGY

The DNDC Model

The Denitrification-Decomposition (DNDC) is a process-based biogeochemical model simulating carbon and nitrogen interactions and cycling in ecological systems (Li et al., 1992; 1994; Li, 2000). Built upon the fundamental biogeochemical processes of decomposition, fermentation, nitrification, and denitrification, the DNDC model incorporates classic laws of physics, chemistry, and biology as well as many empirical equations developed from an extensive scientific literature review. The model consists of three submodels which simulate the mass transfer of heat and water (the thermal-hydraulic submodel), carbon speciation (the decomposition submodel), and nitrogen speciation (the nitrification-denitrification submodel). It is capable of predicting carbon and nitrogen dynamics in ecosystems, including production of trace gases, i.e., carbon dioxide (CO_2), CH_4, N_2O, and NO_X, and NH_3, at the field, regional, or national scale depending on the spatial resolution of the input database that specifies temporal and spatial variations of the basic ecological drivers of crop, soil, meteorology, and management activities.

The DNDC model was initially developed for agroecosystems but was later expanded to cover other ecological systems such as forests (Forest-DNDC), wetlands (Wetland-DNDC), and dairy farms (Manure-DNDC) (Giltrap et al., 2010; Gilhespy et al., 2014). In this analysis, DNDC (version 95) was used for simulating soil NO_X emissions in cropland, grassland and urban turf systems, and Forest-DNDC (version 1.1) was used for forest systems. A schematic representation of the DNDC model is presented in Figure 1. A full description of the DNDC scientific basis and processes, including all equations simulated in calculating soil C and N gaseous emissions, is available at the DNDC host site at the University of New Hampshire (UNH, 2012).

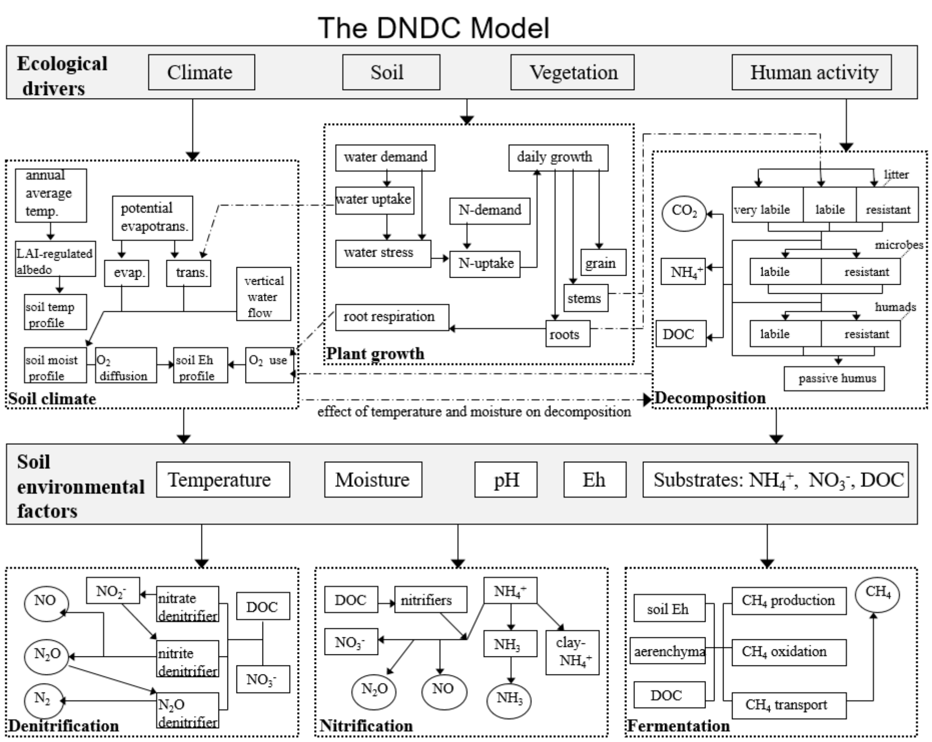

Figure 1. The DNDC framework (UNH, 2012).

Database Development

Because the DNDC model is driven by four primary ecological drivers, i.e., land use, soil, meteorology, and management practices, a spatio-temporal differentiated database was established containing California-specific information on these drivers. The data sources were mainly derived from the public domain such as open literatures, government reports and databases, and institution online data tools.

The land use data was obtained from the Cropland Data Layer (CDL) of the U.S. Department of Agriculture (USDA, 1997-2020). The CDL, rather than the Census of Agriculture data of the USDA for crop acreages (USDA, 2000-2020), was chosen because it provides detailed spatial information on the distribution of land uses. The CDL is a raster, geo-referenced land cover dataset created annually for the continental U.S. using satellite imagery with extensive agricultural ground truthing. The 2017 California CDL used for CEIDARS covered 88 land use classes for California, with a ground resolution of 30 m. Table 1 summarizes the areas of the seven land use categories of the 2017 California CDL, including cropland, developed (urban) land, grassland, forest, shrub land, fallow, and excluded land which included wetlands, open water, and perennial ice/snow systems. NO_X emissions from the excluded land were not simulated because significant NO_X emissions are not expected from the excluded systems due to their lack of specific biophysical conditions required for NO_X formation. For developed land, only emissions from turf grass were simulated. The fraction of turf grass was assumed to be 0.05, 0.08, 0.12, and 0.1 for high-density, low-density, medium-density, and open developed land, respectively, based on a rough assessment of Google satellite maps and the predicted water usage consistent with the statewide water budget for urban use (Natural Resources Defense Council, 2014). Total turf grass acreage was assumed to be 67% residential and 33% commercial based on survey results conducted in the U.S. (Milesi et al., 2009). For forest systems, three types of forest, i.e., deciduous, evergreen and mixed forest, were simulated. The leading tree groups for each forest type per county (Table 2) were identified from forest basin data of the U.S. Forest Service for Western U.S. (USFS, 2011). If information on the leading tree group is unavailable for a county, the prevailing tree group (i.e., the tree group with the largest area) in the immediate neighboring counties were adopted for the analysis.

For CEPAM, besides the CDL data from 2000 to 2020, the land use data from 2021 to 2060 were also required. To forecast land use areas for future years in California, we first examined the linear correlation between the historical land use data and population from 2000 to 2020 for each land use cover, assuming that the land use change was driven by population change. If a significant correlation is identified between a land use cover and the population, the relationship would be extrapolated to post 2020 based on the forecast population of the California Department of Finance (CDOF, 2011; 2021). If a significant correlation is not found, the slope of the land use change between the first (2000) and last year (2020) against the population would be applied to post 2020. We found significant correlation for the three land use covers of urban land, shrub land, and grassland. However, the initial predicted reduction of 70% for grassland from 2020 to 2060 based on the correlation was modified to 47%, because (1) we think the lowered reduction of grassland is more reasonable, and (2) the modified grassland reduction of 47% is necessary to keep the total land area of the State constant. There is no significant correlation for cropland and forest. No growth was assumed for fallow land and excluded land. Figure 2 shows the correlation analysis for the land use covers from 2000 to 2020 and Table 3 presents areas of different land use covers from 2000 to 2060. Based on our analysis, urban land and shrub land would increase by 18.2% and 10.8%, respectively, and cropland, forest and grassland would decrease by 1.9%, 1.6% and 47%, respectively, from 2020 to 2060.

Soil property data were developed from the Soil Survey Geographic Database (SSURGO) of the Natural Resources Conservation Service, USDA (USDA, 2016). SSURGO is a three-dimensional spatial database which contains detailed soil distribution and profile information for the entire U.S. Parameter values of the four soil properties of soil organic carbon (SOC) content, soil density, soil pH, and soil clay fraction were obtained from SSURGO. The area-weighted means of the four soil properties for the topsoil horizon were calculated for cropland, urban land, and forest separately for each county by overlying the polygons of the soil components layer (COMP) from SSURGO with the specific land use covers. For each of the selected soil properties, SSURGO provides low, high and representative values. Representative values of the soil parameters were used in the DNDC model, except for turf grass, for which the SOC value was raised three times that of cropland according to Pouyat et al. (2006), apparently due to intensive management inputs and lack of soil disturbance in turf grass. Table 4 presents soil property values obtained for the three land use covers of cropland, urban land and forest in different California counties. The four basic soil parameters listed in Table 4 were then used as the drivers to establish other soil characteristics, such as soil porosity, saturated hydraulic conductivity, field capacity, wilting point, and specific heat, based on the built-in empirical relations of the DNDC model.

Table 1. Land use cover areas (ha) of the 2017 California Crop Data Layer (USDA, 1997-2020).

County	Cropland	Urban	Grassland	Forest	Shrub land	Fallow	Excluded
Alameda	1868	69072	59904	33768	17382	915	9465
Alpine	156	1420	836	80687	100523	6182	1996
Amador	1430	6634	45679	69793	30056	499	2684
Butte	115557	26433	63618	176320	38365	1088	12897
Calaveras	280	9481	73466	118474	60576	122	5901
Colusa	140742	10092	50299	11830	78380	438	7647
Contra Costa	19137	68385	57571	30066	6894	208	14780
Del Norte	5	12641	6214	208431	29156	310	5585
El Dorado	80	20405	30696	294443	92578	4242	21112
Fresno	527888	88263	218785	340751	259849	107041	15971
Glenn	117519	13397	92108	42159	71342	1976	5158
Humboldt	4182	30871	58796	690409	125123	5813	12043
Imperial	198856	33538	200	342	545376	298320	83779

County	Cropland	Urban	Grassland	Forest	Shrub land	Fallow	Excluded
Inyo	1214	14082	8013	125893	2328429	158555	12806
Kern	435053	127235	439386	103643	898118	98463	9468
Kings	270773	21093	52687	685	8802	1654	4733
Lake	1555	17566	21566	96082	188602	508	18762
Lassen	29547	12488	40397	351524	734512	16725	36688
Los Angeles	4352	358166	70519	53471	525245	41573	4324
Madera	148425	20180	111291	178036	72665	22855	4272
Marin	1630	20676	43175	40418	24255	315	5294
Mariposa	67	5625	94525	158370	109789	6868	3113
Mendocino	4156	46328	62143	537818	253332	923	4802
Merced	225405	33136	178252	6074	19756	3538	44180
Modoc	56151	10242	161450	290940	465727	50319	53712
Mono	1703	5677	25446	179819	530949	41870	25414
Monterey	64678	67527	222562	176330	301827	9820	14960
Napa	15019	13087	27180	50739	83973	227	14456
Nevada	14	11905	11617	174927	49351	466	3905
Orange	11	128834	6527	1263	67956	479	1805
Placer	22801	32017	37075	219082	52790	426	24322
Plumas	6336	7315	15841	467285	161847	93	18552
Riverside	89690	186919	90058	34511	1345870	115975	27691
Sacramento	78331	83852	80092	1574	155	1166	12135
San Benito	13487	16089	138325	35789	150339	5013	871
San Bernardino	2345	185186	25516	93701	4339857	552076	8395
San Diego	420	205487	75562	35802	656990	112284	10614
San Francisco	3	11459	24	324	188	18	200
San Joaquin	230908	49404	66314	2591	7238	788	11704
San Luis Obispo	50621	52446	333754	105652	278576	32714	5904
San Mateo	376	37903	9234	56929	8574	655	3776
Santa Barbara	22105	48328	115032	125413	387220	8726	4339
Santa Clara	5395	91245	51653	106880	75756	158	5790
Santa Cruz	1555	22607	6193	75644	8082	165	1275
Shasta	14798	33714	90263	550903	276960	9613	20104
Sierra	1576	2829	9017	154108	78861	101	2647
Siskiyou	77808	41515	92088	1014654	375004	25094	18008
Solano	78582	30899	60803	7667	7325	502	45128
Sonoma	27602	44853	87730	154372	87617	439	8588
Stanislaus	154745	39375	120247	17750	48493	2037	9730
Sutter	124996	11997	12003	736	1782	57	6023
Tehama	32075	23459	296473	180271	225479	2748	6313
Trinity	44	23386	12068	567234	217009	2154	9047

County	Cropland	Urban	Grassland	Forest	Shrub land	Fallow	Excluded
Tulare	309156	42476	184204	361421	287424	65536	3648
Tuolumne	26	8058	49733	287179	183925	48534	12431
Ventura	2455	64572	35084	84476	277865	11050	7507
Yolo	159894	17616	39785	6263	36660	399	3991
Yuba	47482	10506	32155	64055	6301	2051	4211
Grand Total	3943064	2729992	4501232	9435771	17703075	1882887	754656

a. Excluded land includes wetlands, open water, and perennial ice and snow, which do not produce NO_X due to their biophysical conditions.

Table 2. Leading forest tree type groups based on area for California counties (USFS, 2011).

County	Deciduous	Evergreen	Mixed
Alameda	Western Larch Group	Tanoak/Laurel Group	
Alpine	Aspen/Birch Group	Fir/Spruce/Mountain Hemlock Group	California Mixed Conifer Group
Amador	Western Larch Group	Lodgepole Pine Group	California Mixed Conifer Group
Butte	Western Larch Group	Fir/Spruce/Mountain Hemlock Group	California Mixed Conifer Group
Calaveras	Western Larch Group	Fir/Spruce/Mountain Hemlock Group	California Mixed Conifer Group
Colusa	Western Larch Group	Fir/Spruce/Mountain Hemlock Group	California Mixed Conifer Group
Contra Costa	Western Larch Group	Tanoak/Laurel Group	
Del Norte	Redwood Group	Douglas-fir Group	California Mixed Conifer Group
El Dorado	Western Larch Group	Fir/Spruce/Mountain Hemlock Group	California Mixed Conifer Group
Fresno	Western Larch Group	Lodgepole Pine Group	California Mixed Conifer Group
Glenn	Western Larch Group	Fir/Spruce/Mountain Hemlock Group	California Mixed Conifer Group
Humboldt	Redwood Group	Tanoak/Laurel Group	California Mixed Conifer Group
Imperial		Pinyon/Juniper Group	Other Western Hardwoods Group
Inyo	Aspen/Birch Group	Pinyon/Juniper Group	Other Western Softwood Group
Kern[a]	Western Larch Group	Lodgepole Pine Group	California Mixed Conifer Group
Kings[a]	Western Larch Group		
Lake	Western Larch Group	Ponderosa Pine Group	California Mixed Conifer Group
Lassen	Western Larch Group	Ponderosa Pine Group	California Mixed Conifer Group
Los Angeles	Western Larch Group	Ponderosa Pine Group	California Mixed Conifer Group
Madera	Western Larch Group	Fir/Spruce/Mountain Hemlock Group	California Mixed Conifer Group
Marin	Redwood Group	Douglas-fir Group	Other Western Softwood Group
Mariposa	Western Larch Group	Fir/Spruce/Mountain Hemlock Group	California Mixed Conifer Group
Mendocino	Western Larch Group	Tanoak/Laurel Group	California Mixed Conifer Group
Merced	Western Larch Group		
Modoc	Western Larch Group	Ponderosa Pine Group	California Mixed Conifer Group
Mono	Aspen/Birch Group	Pinyon/Juniper Group	Other Western Softwood Group

County	Deciduous	Evergreen	Mixed
Monterey	Western Larch Group	Tanoak/Laurel Group	Other Western Hardwoods Group
Napa	Western Larch Group	Tanoak/Laurel Group	California Mixed Conifer Group
Nevada	Western Larch Group	Fir/Spruce/Mountain Hemlock Group	California Mixed Conifer Group
Orange	Western Larch Group		
Placer	Western Larch Group	Fir/Spruce/Mountain Hemlock Group	California Mixed Conifer Group
Plumas	Western Larch Group	Ponderosa Pine Group	California Mixed Conifer Group
Riverside	Western Larch Group	Ponderosa Pine Group	California Mixed Conifer Group
Sacramento	Western Larch Group		
San Benito	Western Larch Group		
San Bernardino	Western Larch Group	Pinyon/Juniper Group	California Mixed Conifer Group
San Diego	Western Larch Group	Ponderosa Pine Group	California Mixed Conifer Group
San Francisco	Western Larch Group	Ponderosa Pine Group	
San Joaquin	Western Larch Group		
San Luis Obispo	Western Larch Group	Tanoak/Laurel Group	Exotic Hardwoods Group
San Mateo	Redwood Group	Tanoak/Laurel Group	Other Western Softwood Group
Santa Barbara	Western Larch Group	Ponderosa Pine Group	Other Western Hardwoods Group
Santa Clara	Western Larch Group	Tanoak/Laurel Group	Other Western Softwood Group
Santa Cruz	Western Larch Group	Tanoak/Laurel Group	Other Western Softwood Group
Shasta	Western Larch Group	Ponderosa Pine Group	California Mixed Conifer Group
Sierra	Western Larch Group	Ponderosa Pine Group	California Mixed Conifer Group
Siskiyou	Western Larch Group	Ponderosa Pine Group	Other Western Hardwoods Group
Solano	Western Larch Group	Douglas-fir Group	Other Western Hardwoods Group
Sonoma	Western Larch Group	Tanoak/Laurel Group	Other Western Hardwoods Group
Stanislaus	Western Larch Group		
Sutter	Western Larch Group		
Tehama	Western Larch Group	Fir/Spruce/Mountain Hemlock Group	California Mixed Conifer Group
Trinity	Western Larch Group	Fir/Spruce/Mountain Hemlock Group	California Mixed Conifer Group
Tulare	Western Larch Group	Lodgepole Pine Group	California Mixed Conifer Group
Tuolumne	Western Larch Group	Lodgepole Pine Group	California Mixed Conifer Group

County	Deciduous	Evergreen	Mixed
Ventura	Western Larch Group	Ponderosa Pine Group	California Mixed Conifer Group
Yolo	Western Larch Group		California Mixed Conifer Group
Yuba	Western Larch Group	Tanoak/Laurel Group	

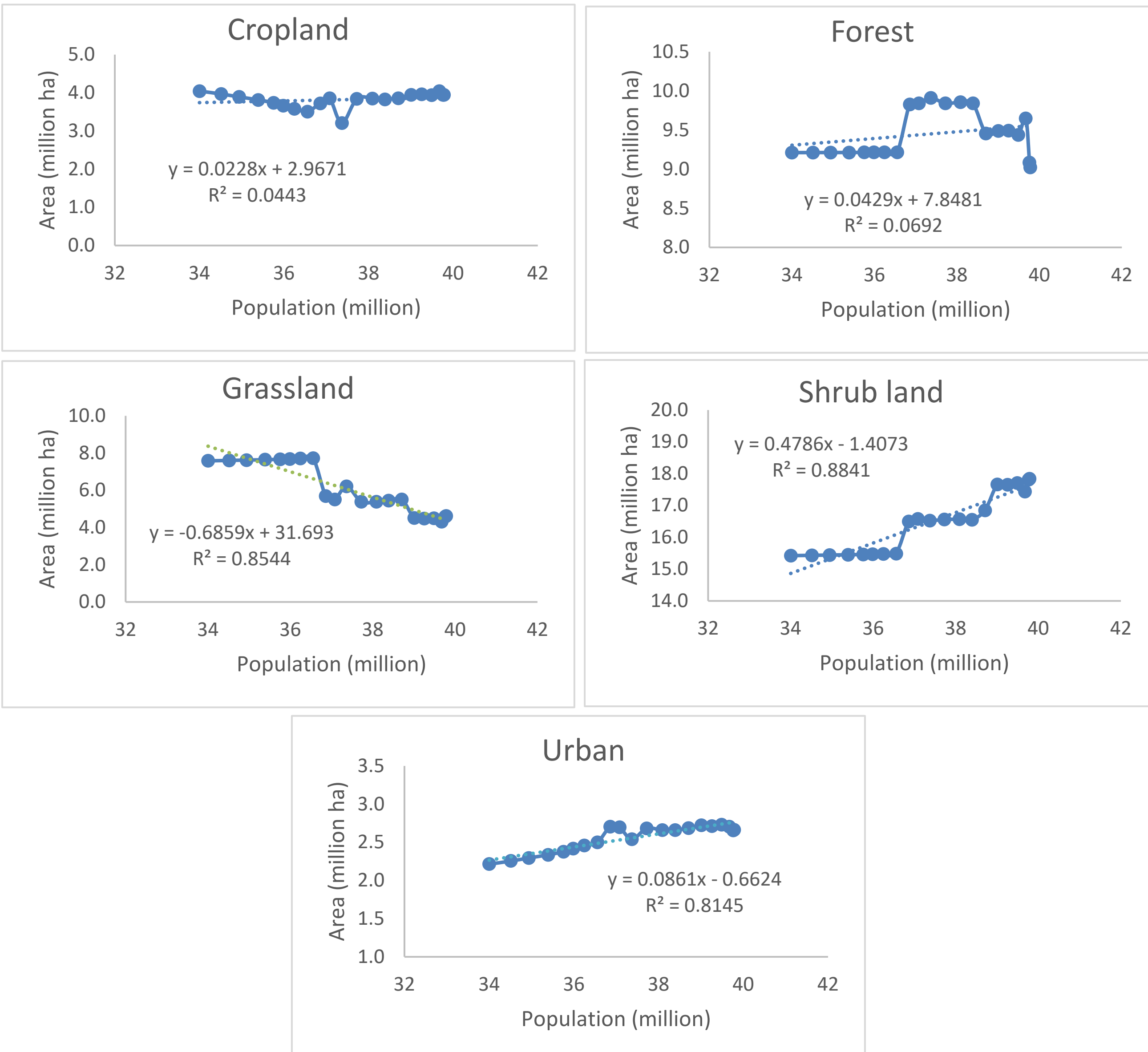

Figure 2. Linear regression analysis of land use cover areas (USDA, 1997-2020) against population (CDOF, 2011; 2021) in California from 2000 to 2020.

Table 3. Land use cover areas (ha) of 2000 to 2060 based on California Crop Data Layer (USDA, 1997-2020) and forecast population (CDOF, 2011; 2021).

Year	Population	Cropland	Urban	Grassland	Forest	Shrubland	Fallow[a]	Excluded[a]
2000	34000834	4045347	2213552	7583905	9211577	15423363	1768116	703400
2001	34512741	3968744	2254148	7603960	9212107	15432619	1773411	704270
2002	34938290	3892141	2294744	7624015	9212638	15441875	1778706	705140
2003	35388929	3815538	2335340	7644070	9213169	15451132	1784001	706010
2004	35752766	3738935	2375936	7664125	9213699	15460388	1789296	706880
2005	35985582	3662332	2416532	7684181	9214230	15469644	1794591	707750
2006	36246821	3585729	2457128	7704236	9214761	15478900	1799886	708620
2007	36552531	3509128	2497724	7724293	9215292	15488157	1805181	709500
2008	36856223	3724648	2705016	5693633	9826668	16495483	1791319	713445
2009	37077204	3860880	2694944	5505583	9841085	16579372	1778450	689943
2010	37366938	3206519	2539340	6204666	9911449	16524937	1776003	784989
2011	37721469	3845539	2682109	5388505	9840926	16557355	1859159	773759
2012	38088010	3854113	2658390	5381716	9857440	16568907	1844434	783660
2013	38389173	3831848	2660004	5444291	9840476	16556905	1848186	767918
2014	38705642	3857694	2685911	5512807	9454228	16845264	1849017	744627
2015	39007121	3947706	2721231	4506623	9488026	17665112	1875425	746567
2016	39254338	3965578	2711243	4484718	9491205	17656077	1879770	762199
2017	39488428	3943064	2729992	4501232	9435771	17703075	1882887	754671
2018	39670351	4044102	2705289	4317935	9648714	17436820	1987217	810719
2019	39761195	3950869	2656215	4588018	9084178	17818541	2003195	849748
2020	39782420	3948006	2663297	4622248	9023041	17839542	1998521	856924
2021	39953269	3945129	2778313	4640590	9017469	17714631	1998521	856909
2022	40146002	3941884	2794845	4541279	9011184	17806941	1998521	856909
2023	40354217	3938379	2812704	4433990	9004395	17906665	1998521	856909
2024	40574215	3934675	2831574	4320630	8997221	18012034	1998521	856909
2025	40808001	3930739	2851626	4200165	8989597	18124006	1998521	856909
2026	41028749	3927022	2870561	4086418	8982398	18229734	1998521	856909

Year	Population	Cropland	Urban	Grassland	Forest	Shrubland	Fallow[a]	Excluded[a]
2027	41245009	3923381	2889110	3974984	8975346	18333312	1998521	856909
2028	41456076	3919828	2907214	3866225	8968463	18434403	1998521	856909
2029	41660700	3916382	2924765	3760787	8961791	18532408	1998521	856909
2030	41860549	3913018	2941907	3657809	8955274	18628126	1998521	856909
2031	42050984	3909811	2958241	3559682	8949064	18719335	1998521	856909
2032	42231576	3906771	2973731	3466627	8943174	18805830	1998521	856909
2033	42403084	3903883	2988442	3378252	8937582	18887974	1998521	856909
2034	42565496	3901149	3002373	3294565	8932285	18965761	1998521	856909
2035	42718403	3898575	3015488	3215775	8927299	19038996	1998521	856909
2036	42862413	3896150	3027840	3141570	8922603	19107970	1998521	856909
2037	42998578	3893857	3039519	3071407	8918163	19173187	1998521	856909
2038	43126054	3891711	3050453	3005721	8914006	19234242	1998521	856909
2039	43243461	3889734	3060524	2945224	8910177	19290474	1998521	856909
2040	43353413	3887883	3069955	2888568	8906592	19343136	1998521	856909
2041	43454655	3886179	3078639	2836400	8903290	19391626	1998521	856909
2042	43548719	3884595	3086707	2787931	8900223	19436678	1998521	856909
2043	43634901	3883144	3094099	2743523	8897412	19477955	1998521	856909
2044	43713905	3881814	3100875	2702814	8894836	19515794	1998521	856909
2045	43785945	3880601	3107054	2665693	8892487	19550298	1998521	856909
2046	43850632	3879512	3112603	2632361	8890378	19581279	1998521	856909
2047	43909257	3878525	3117631	2602153	8888466	19609358	1998521	856909
2048	43961292	3877649	3122095	2575340	8886769	19634280	1998521	856909
2049	44008766	3876850	3126167	2550878	8885221	19657018	1998521	856909
2050	44049015	3876172	3129619	2530139	8883908	19676295	1998521	856909
2051	44083766	3875587	3132600	2512232	8882775	19692939	1998521	856909
2052	44113373	3875088	3135139	2496976	8881810	19707120	1998521	856909
2053	44139270	3874652	3137360	2483632	8880965	19719523	1998521	856909
2054	44160169	3874300	3139153	2472863	8880284	19729533	1998521	856909
2055	44176738	3874021	3140574	2464326	8879743	19737468	1998521	856909
2056	44189862	3873801	3141700	2457563	8879315	19743754	1998521	856909

Year	Population	Cropland	Urban	Grassland	Forest	Shrubland	Fallow[a]	Excluded[a]
2057	44200258	3873625	3142591	2452206	8878976	19748733	1998521	856909
2058	44210827	3873448	3143498	2446760	8878632	19753795	1998521	856909
2059	44220894	3873278	3144361	2441573	8878303	19758617	1998521	856909
2060	44228056	3873157	3144976	2437883	8878070	19762047	1998521	856909
Change (2020 to 2060)	11.2%	-1.9%	18.1%	-47.3%	-1.6%	10.8%	0.0%	0.0%

Table 4. Major soil properties per land use cover in California counties used in the DNDC modeling based on the USDA's SSURGO soil database (USDA, 2016).

	Cropland				Urban land (turf)				Forest			
County	SOC, fraction	Clay, fraction	pH	Bulk density, g cm^{-3}	SOC, fraction	Clay, fraction	pH	Bulk density, g cm^{-3}	SOC, fraction	Clay, fraction	pH	Bulk density, g cm^{-3}
Alameda	0.0099	0.284	6.45	1.38	0.0297	0.2901	6.98	1.51	0.0139	0.2462	6.54	1.52
Alpine	0.0185	0.139	6.47	1.34	0.0556	0.1083	6.22	1.33	0.0232	0.0947	6.09	1.30
Amador	0.0096	0.148	6.12	1.53	0.0287	0.1371	5.54	1.21	0.0222	0.1562	6.05	1.32
Butte	0.0155	0.372	5.28	1.35	0.0466	0.2377	6.55	1.52	0.0122	0.1865	6.06	1.37
Calaveras	0.0053	0.13	6.37	1.47	0.0158	0.1770	6.13	1.40	0.0196	0.1656	6.07	1.30
Colusa	0.0110	0.302	6.6	1.44	0.0329	0.2945	7.09	1.52	0.0151	0.1949	6.10	1.51
Contra Costa	0.0080	0.331	7.06	1.46	0.0240	0.3006	6.95	1.52	0.0149	0.2680	6.55	1.52
Del Norte	0.0693	0.24	5.12	1.08	0.0693[a]	0.1922	6.12	1.48	0.0201	0.2136	5.97	1.38
El Dorado	0.0116	0.165	6.05	1.38	0.0348	0.1534	6.18	1.42	0.0228	0.1475	6.05	1.29
Fresno	0.0056	0.238	7.15	1.48	0.0168	0.1569	7.01	1.58	0.0190	0.1012	6.09	1.38
Glenn	0.0093	0.305	6.27	1.45	0.0279	0.2037	6.77	1.57	0.0159	0.1929	5.85	1.45
Humboldt	0.0232	0.226	6.13	1.46	0.0697	0.1928	6.03	1.47	0.0198	0.2022	5.93	1.39

County	Cropland				Urban land (turf)				Forest			
	SOC, fraction	Clay, fraction	pH	Bulk density, g cm^{-3}	SOC, fraction	Clay, fraction	pH	Bulk density, g cm^{-3}	SOC, fraction	Clay, fraction	pH	Bulk density, g cm^{-3}
Imperial	0.0031	0.317	8.09	1.5	0.0092	0.2881	6.98	1.50	0.0028	0.1682	8.14	1.29
Inyo	0.0090	0.119	6.76	1.47	0.0271	0.0961	8.12	1.57	0.0105	0.1003	7.04	1.53
Kern	0.0035	0.192	7.33	1.52	0.0104	0.1612	7.72	1.59	0.0108	0.1363	6.72	1.53
Kings	0.0056	0.184	7.57	1.52	0.0167	0.2407	7.90	1.37	0.0120	0.2933	7.03	1.49
Lake	0.0108	0.224	6.42	1.49	0.0325	0.2244	6.37	1.41	0.0139	0.2002	6.21	1.45
Lassen	0.0125	0.238	7	1.37	0.0376	0.2095	7.27	1.46	0.0136	0.1439	6.41	1.44
Los Angeles	0.0060	0.142	6.54	1.5	0.0180	0.1633	6.96	1.59	0.0082	0.1193	6.50	1.58
Madera	0.0047	0.125	6.61	1.55	0.0142	0.1303	6.84	1.60	0.0178	0.1124	6.14	1.42
Marin	0.0152	0.196	6.03	1.49	0.0456	0.2834	6.46	1.50	0.0145	0.2268	6.16	1.52
Mariposa	0.0152	0.191	6	1.45	0.0455	0.1764	6.14	1.46	0.0163	0.1350	6.12	1.42
Mendocino	0.0166	0.239	6.2	1.43	0.0497	0.1772	6.11	1.50	0.0156	0.1869	6.02	1.45
Merced	0.0060	0.199	6.82	1.52	0.0180	0.1890	7.17	1.56	0.0118	0.2392	6.76	1.50
Modoc	0.0118	0.225	6.89	1.4	0.0353	0.2042	7.08	1.36	0.0159	0.1672	6.54	1.35
Mono	0.0195	0.13	6.71	1.32	0.0586	0.1244	6.65	1.41	0.0140	0.1022	6.70	1.44
Monterey	0.0132	0.214	6.61	1.43	0.0396	0.1843	6.87	1.52	0.0150	0.1872	6.63	1.55
Napa	0.0118	0.239	6.06	1.41	0.0355	0.2645	6.53	1.46	0.0155	0.2338	6.37	1.41
Nevada	0.0207	0.174	6.1	1.25	0.0621	0.1472	6.11	1.36	0.0223	0.1555	6.08	1.32
Orange	0.0103	0.219	6.9	1.5	0.0308	0.1790	6.95	1.58	0.0072	0.1712	6.51	1.56
Placer	0.0072	0.151	6.04	1.53	0.0217	0.1570	6.47	1.57	0.0235	0.1476	6.04	1.28
Plumas	0.0131	0.15	6.45	1.52	0.0393	0.1492	6.36	1.39	0.0168	0.1353	6.20	1.38
Riverside	0.0052	0.171	7.09	1.54	0.0155	0.1005	7.32	1.63	0.0079	0.1238	6.47	1.59
Sacramento	0.0065	0.223	6.18	1.53	0.0194	0.2068	6.59	1.57	0.0083	0.1742	6.19	1.56
San Benito	0.0146	0.289	7.07	1.48	0.0439	0.2522	7.24	1.48	0.0001	0.2634	6.88	1.48
San Bernardino	0.0067	0.107	6.74	1.45	0.0200	0.1078	7.21	1.62	0.0079	0.1214	6.64	1.57
San Diego	0.0062	0.144	6.19	1.54	0.0187	0.1688	6.50	1.59	0.0129	0.1300	6.46	1.51

County	Cropland				Urban land (turf)				Forest			
	SOC, fraction	Clay, fraction	pH	Bulk density, g cm^{-3}	SOC, fraction	Clay, fraction	pH	Bulk density, g cm^{-3}	SOC, fraction	Clay, fraction	pH	Bulk density, g cm^{-3}
San Francisco	0.0174	0.255	6.75	1.4	0.0522	0.2042	6.40	1.58	0.0103	0.1133	6.12	1.62
San Joaquin	0.0098	0.236	6.74	1.51	0.0293	0.2503	7.07	1.56	0.0137	0.1949	6.81	1.55
San Luis Obispo	0.0116	0.26	6.81	1.48	0.0347	0.2148	6.74	1.54	0.0136	0.2444	6.79	1.50
San Mateo	0.0131	0.231	5.91	1.45	0.0394	0.3127	6.51	1.51	0.0156	0.1972	6.30	1.49
Santa Barbara	0.0118	0.17	6.24	1.51	0.0355	0.1458	6.71	1.57	0.0113	0.1983	6.63	1.52
Santa Clara	0.0128	0.338	6.84	1.41	0.0385	0.2891	6.61	1.46	0.0117	0.2111	6.56	1.51
Santa Cruz	0.0133	0.175	6.48	1.5	0.0400	0.1722	6.64	1.53	0.0165	0.1578	6.45	1.46
Shasta	0.0136	0.216	6.11	1.41	0.0408	0.1994	6.08	1.51	0.0236	0.1564	6.13	1.27
Sierra	0.0144	0.188	6.45	1.4	0.0433	0.1425	6.43	1.39	0.0226	0.1426	6.05	1.25
Siskiyou	0.0096	0.178	6.52	1.39	0.0287	0.1602	6.50	1.29	0.0191	0.1395	6.15	1.34
Solano	0.0094	0.353	6.53	1.46	0.0282	0.2970	6.75	1.51	0.0125	0.2330	6.47	1.46
Sonoma	0.0122	0.235	5.74	1.44	0.0366	0.2507	6.27	1.51	0.0147	0.2007	6.05	1.45
Stanislaus	0.0062	0.186	6.7	1.53	0.0187	0.1380	6.93	1.60	0.0119	0.2057	6.93	1.54
Sutter	0.0094	0.329	6.76	1.44	0.0281	0.2909	7.14	1.51	0.0109	0.1540	6.76	1.52
Tehama	0.0092	0.203	6.33	1.48	0.0276	0.2072	6.52	1.55	0.0228	0.1711	5.98	1.33
Trinity	0.0110	0.211	6.42	1.42	0.0330	0.1879	6.34	1.43	0.0172	0.1718	6.13	1.45
Tulare	0.0072	0.205	7.21	1.5	0.0217	0.1311	7.16	1.62	0.0169	0.1061	6.19	1.41
Tuolumne	0.0172	0.194	5.86	1.26	0.0516	0.1632	6.09	1.39	0.0216	0.1184	6.01	1.32
Ventura	0.0124	0.218	6.9	1.47	0.0373	0.1690	7.28	1.56	0.0098	0.1832	6.79	1.52
Yolo	0.0100	0.316	6.71	1.46	0.0300	0.2724	6.90	1.51	0.0096	0.2520	6.55	1.52
Yuba	0.0079	0.219	6.3	1.48	0.0238	0.2099	6.43	1.56	0.0155	0.1767	6.15	1.39

a. SOC for Del Norte was not raised due to the high cropland SOC value due to organic farming.

The meteorological data were obtained from the DAYMET model (Thornton et al., 2015). DAYMET provides gridded estimates of selected weather parameters for North America at 1x1 km^2 resolution, derived from existing meteorological observations using a collection of interpolating and extrapolating algorithms. For each of the 58 counties in California, the daily precipitation, minimum and maximum temperatures, and solar radiation were generated from DAYMET based on the county centroids for years from 1998 to 2020, and the average of the last ten years (2011-2020) was then taken for years post 2020. In addition, depth to groundwater table (DTG), which was required for forest simulation, was estimated from groundwater level measurements of California Department of Water Resources (CDWR, 2018) using the 2012 data. Table 5 provides the county coordinates and the estimated DTG for California counties used in the model.

Farming management data, including planting and harvest dates, tillage, fertilization, irrigation, and residue management, were developed for 55 cropping systems represented in the DNDC model. Table 6 lists the key crop physiological parameters of the 55 cropping systems, calibrated where possible for California-specific field observations. The management data were obtained largely from open literature and surveys. Nitrogen fertilizer use (rates, types, and schedule) was based on the “Cost and Return Studies” reported by the University of California, Davis (UCD, 2015) and literature reviews (Rosenstock et al., 2013). Table 7 shows the fertilizer application rates used in the DNDC model.

Irrigation methods for the crops were assumed to change over time per the Statewide Irrigation Methods Surveys of the California Department of Water Resources (CDWR, 2015). The four irrigation methods modeled were surface gravity irrigation (flooding), sprinkler irrigation, surface drip, and subsurface drip. Fractions of irrigation methods for each crop were developed using linear interpolation or extrapolation from 2000 and 2010 survey results (Table 8). The baseline irrigation method and corresponding irrigation water depth for each crop were first determined from the "Cost and Return Studies" (UCD, 2015). The baseline irrigation depth was then varied using factors of 1.58, 1.27, 1.06, and 1.0 for flooding, sprinkler irrigation, surface drip, and subsurface drip, respectively, according to the reported water use efficiencies of 60%, 75%, 90%, and 95% for the four irrigation methods, respectively (Brouwer et al. 1989). The final irrigation depth was further adjusted for each county based on the ratio of the county’s annual mean air temperature to the state-mean air temperature so that more irrigation water would be applied for counties with higher air temperatures.

Finally, the types of crops cultivated in California dairy farms were compiled from 127 dairy farms sampled randomly from 2013 Annual Dairy Reports of California’s Regional Water Quality Control Boards (RWQCB) (C. Herbst, Nov. 18, 2014, personal communication), covering 10% of the total number of dairy farms in the Central Valley of California. The Geographic Information System (GIS) data on spatial distribution of the dairy farms was obtained from RWQCB (C. Herbst et al., Sep. 3, 2015, personal communication). The land application of manure and fertilizer nitrogen to silage crops was based on Burger and Horwath (2013). Only manure that was applied to corn silage was included in the model, with an average application rate of 434.7 kgN ha^{-1} and 191.7 kgN ha^{-1} for manure and fertilizer, respectively. The total amount of manure

N applied to corn silage was calculated to be 71,108 metric tons (MT) in 2017 (Table 9), which was about 16% of the manure N excreted by cattle in California (USDA, 2000-2020; CARB, 2020). The manure application in corn silage was removed from dairy farms for soil NH_3 simulation to avoid double counting of NH_3 emissions in the CEIDARS and CEPAM inventories.

Management practices for turf grass in developed land included fertilization, irrigation, and grass cutting. The average of the recommended fertilization rates (UCD, 2014) was used for commercial turf grass (170.8 kgN $ha^{-1}y^{-1}$), and 75% of the average rate for residential turf grass (128 kgN $ha^{-1}y^{-1}$). The irrigation practice was implemented using the irrigation index of the DNDC model, which was set at 1.2 and 0.85 for commercial and residential turf grass, respectively. The irrigation index indicates the amount of water provided to the turf grass to meet the predicted water deficit. An index of one means a perfect match between water supply and water demand, >1 means over supply, and < 1 means under-supply. The grass cutting was assumed weekly for commercial turf grass and biweekly for residential turf grass. No management activities were implemented for forest.

Table 5. The centroids coordinates and depth to groundwater (DTG) of California counties.

County	FIPS	Latitude, degree	Longitude, degree	Depth to groundwater, m[a]
Alameda	6001	37.648	-121.913	11.14
Alpine	6003	38.618	-119.799	8.85
Amador	6005	38.444	-120.654	8.85
Butte	6007	39.666	-121.602	10.66
Calaveras	6009	38.188	-120.555	22.35
Colusa	6011	39.178	-122.238	10.79
Contra Costa	6013	37.919	-121.952	5.35
Del Norte	6015	41.750	-123.981	5.43
El Dorado	6017	38.786	-120.534	8.85
Fresno	6019	36.761	-119.655	47.49
Glenn	6021	39.603	-122.402	14.7
Humboldt	6023	40.707	-123.926	6.03
Imperial	6025	33.041	-115.355	83.78
Inyo	6027	36.562	-117.404	288.68
Kern	6029	35.347	-118.730	76.97
Kings	6031	36.072	-119.816	59.07
Lake	6033	39.095	-122.747	6.95
Lassen	6035	40.721	-120.630	11.8
Los Angeles	6037	34.196	-118.262	67.95
Madera	6039	37.210	-119.750	50.6
Marin	6041	38.052	-122.746	1.52
Mariposa	6043	37.570	-119.913	14.09

County	FIPS	Latitude, degree	Longitude, degree	Depth to groundwater, m[a]
Mendocino	6045	39.432	-123.443	6.1
Merced	6047	37.195	-120.723	24.96
Modoc	6049	41.593	-120.718	15.31
Mono	6051	37.916	-118.875	30.71
Monterey	6053	36.240	-121.316	17.7
Napa	6055	38.507	-122.326	11.57
Nevada	6057	39.295	-120.773	28.19
Orange	6059	33.676	-117.777	23.71
Placer	6061	39.062	-120.723	28.9
Plumas	6063	39.995	-120.830	13.9
Riverside	6065	33.730	-116.002	62.49
Sacramento	6067	38.450	-121.340	22.82
San Benito	6069	36.611	-121.085	17.7
San Bernardino	6071	34.857	-116.181	36.61
San Diego	6073	33.024	-116.776	14.76
San Francisco	6075	37.727	-123.032	5.7
San Joaquin	6077	37.935	-121.272	24.23
San Luis Obispo	6079	35.385	-120.448	20.6
San Mateo	6081	37.415	-122.372	5.7
Santa Barbara	6083	34.537	-120.038	18.78
Santa Clara	6085	37.221	-121.691	22.35
Santa Cruz	6087	37.012	-122.007	22.91
Shasta	6089	40.761	-122.044	18.92
Sierra	6091	39.577	-120.522	11.5
Siskiyou	6093	41.588	-122.533	12.55
Solano	6095	38.267	-121.940	13.36
Sonoma	6097	38.533	-122.945	13.36
Stanislaus	6099	37.562	-121.003	22.35
Sutter	6101	39.035	-121.703	5.65
Tehama	6103	40.126	-122.232	18.48
Trinity	6105	40.648	-123.114	6.03
Tulare	6107	36.230	-118.781	50.32
Tuolumne	6109	38.021	-119.965	28.55
Ventura	6111	34.359	-119.133	22.76
Yolo	6113	38.679	-121.903	14.13
Yuba	6115	39.270	-121.344	9.9

a. Based on groundwater level measurements of 2012 (CDWR, 2018).

Table 6. DNDC crop physiological parameters.

Crop	Representative productivity[a], kgC	C/N[b]	Representative yield, kgC	Total degree-days[c], °C	Water demand[d]	N fixation index
Alfalfa	13000	14	6500	2000	300	4.00
Almonds	2980	19	894	4000	150	1.00
Apples	4517	42	1355	3000	550	1.00
Apricots	3073	42	922	2000	550	1.00
Artichokes	1328	31	863	1400	500	1.00
Asparagus	326	31	212	1000	500	1.00
Avocados	2233	42	670	3000	550	1.00
Barley	4750	64	1425	1300	250	1.00
Beans_dry	2528	19	910	1900	300	2.00
Beans_green	2872	19	1034	1900	300	2.00
Beets	8990	70	449.5	2550	318	1.00
Berries	4518	26	2259	1400	800	1.00
Broccoli	1460	14	438	1000	150	1.00
Cabbage	1700	22	17	1000	450	1.00
Carrots	3194	31	2076	1400	500	1.00
Cauliflower	737	31	479	1000	500	1.00
Celery	3800	14	38	1300	500	1.00
Cherries	3220	42	966	1000	500	1.00
Citrus_other	5247	42	1574	3000	550	1.00
Corn_grain	9111	50	4100	3000	150	1.00
Corn_silage	8182	49	4500	2500	150	1.00
Cotton	2006	22	642	2500	400	1.00
Dates	10922	38	4915	3000	550	1.00
Figs	1253	42	376	3000	550	1.00
Fruit_other	5020	38	2259	3000	550	1.00
Garlic	4544	28	2272	2550	235	1.00
Grapes	3130	23	1252	1600	350	1.00
Lemons	8050	42	2415	3000	550	1.00
Lettuce	1209	14	774	900	800	1.00
Melons	1995	22	1097	1500	500	1.00
Non_legume_hay	5600	82	2800	2500	550	2.00
Nuts_other	3130	24	1252	3000	150	1.00
Oats	7057	57	2117	1000	250	1.00
Olives	3137	42	941	3000	550	1.00
Onions	4544	28	2272	2550	235	1.00
Pasture	2800	37	1400	2500	550	1.50

Crop	Representative productivity[a], kgC	C/N[b]	Representative yield, kgC	Total degree-days[c], °C	Water demand[d]	N fixation index
Peach	5020	38	2259	3000	550	1.00
Pears	7116	38	3202	3000	550	1.00
Peppers	1982	31	1288	1000	500	1.00
Pistachios	3130	24	1252	3000	150	1.00
Plums	4153	42	1246	3000	550	1.00
Potatoes	5830	59	4081	2100	415	1.00
Prunes	6276	38	2824	3000	550	1.00
Rice	7736	48	3481	3200	508	1.05
Safflowers	6081	42	973	1000	300	1.00
Shrub	2400	144	24	3000	250	1.00
Sorghum	8600	56	3010	2600	200	1.00
Spinach	812	31	528	900	500	1.00
Squash	1995	22	1097	1500	500	1.00
Sunflowers	1610	22	483	1500	495	1.00
Sweet_potatoes	4303	59	3012	2100	415	1.00
Tomatoes	4611	28	1660	1400	900	1.00
Vegetables_other	1209	14	774	900	800	1.00
Wheat_spring	6712	61	2752	1000	200	1.00
Wheat_winter	6712	61	2752	1000	200	1.00

a. Representative productivity of plant biomass (in dry matter kgC ha^{-1}).
b. C/N: Carbon to nitrogen ratio of the plant biomass.
c. Total degree-days: The required cumulative air temperature sum (in °C-days) above the 0 °C threshold during the growing period for full crop growth.
d. Water demand: The amount of water required by the crop to produce per unit dry matter (in g water g^{-1} dry matter).

Table 7. Crop-specific nitrogen application rates used in the DNDC model for California cropland.

Crop	Nitrogen applied, kgN ha^{-1}	Crop	Nitrogen applied, kgN ha^{-1}
Alfalfa	16.8	Lemons	142
Almonds	224	Lettuce	211
Apples	47.1	Melons	196
Apricots	84.1	Non_legume_hay	157
Artichokes	241	Nuts_other	225
Asparagus	100.9	Oats	73.4
Avocados	184.8	Olives	112

Crop	Nitrogen applied, kgN ha^{-1}	Crop	Nitrogen applied, kgN ha^{-1}
Barley	99.8	Onions	242
Beans_dry	101	Pasture	100
Beans_green	144	Peaches	169
Beets	210	Pears	179
Berries	179	Peppers	308
Broccoli	196	Pistachios	196
Cabbage	274	Plums	140
Carrots	280	Potatoes	235
Cauliflower	275	Prunes	168
Celery	271.2	Rice	143
Cherries	68.4	Safflowers	112
Citrus_other	124	Sorghum	157
Corn_grain	291.2	Spinach	156.7
Corn_silage	626[a]	Squash	324
Cotton	203	Sunflowers	100.9
Dates	276	Sweet_potatoes	141
Figs	112.1	Tomatoes	192
Fruit_other	169	Vegetables_other	211
Garlic	283.3	Wheat_spring	336
Grapes	45	Wheat_winter	247

a. Nitrogen application rate for Corn_silage included both manure (434.7 kgN ha^{-1}) and synthetic fertilizer (191.7 kgN ha^{-1}).

Table 8. Historical irrigation practices (fraction of irrigation method) for California crops based on CDWR (2015).

Crop	2000			2020			2060		
	Flooding	Sprinkler	Dripping (surface/ subsurface)	Flooding	Sprinkler	Dripping (surface/ subsurface)	Flooding	Sprinkler	Dripping (surface/ subsurface)
Alfalfa	0.809	0.170	0.022	0.735	0.182	0.083	0.568	0.258	0.174
Almonds	0.192	0.113	0.695	0.068	0.171	0.761	0.000	0.226	0.774
Apples	0.343	0.316	0.341	0.288	0.230	0.482	0.148	0.026	0.825
Apricots	0.343	0.316	0.341	0.288	0.230	0.482	0.148	0.026	0.825
Artichokes	0.380	0.372	0.248	0.111	0.433	0.455	0.000	0.419	0.581
Asparagus	0.380	0.372	0.248	0.111	0.433	0.455	0.000	0.419	0.581
Avocados	0.102	0.128	0.770	0.007	0.175	0.819	0.000	0.172	0.828
Barley	0.874	0.106	0.020	0.698	0.159	0.143	0.445	0.227	0.329
Beans_dry	0.569	0.431	0.000	0.746	0.000	0.254	0.623	0.000	0.377
Beans_green	0.569	0.431	0.000	0.746	0.000	0.254	0.623	0.000	0.377
Beets	0.986	0.013	0.001	0.695	0.063	0.242	0.451	0.000	0.549
Berries	0.380	0.372	0.248	0.111	0.433	0.455	0.000	0.419	0.581
Broccoli	0.380	0.372	0.248	0.111	0.433	0.455	0.000	0.419	0.581
Cabbage	0.380	0.372	0.248	0.111	0.433	0.455	0.000	0.419	0.581
Carrots	0.380	0.372	0.248	0.111	0.433	0.455	0.000	0.419	0.581
Cauliflower	0.380	0.372	0.248	0.111	0.433	0.455	0.000	0.419	0.581
Celery	0.380	0.372	0.248	0.111	0.433	0.455	0.000	0.419	0.581
Cherries	0.343	0.316	0.341	0.288	0.230	0.482	0.148	0.026	0.825
Citrus_other	0.102	0.128	0.770	0.007	0.175	0.819	0.000	0.172	0.828
Corn_grain	0.883	0.007	0.110	0.687	0.012	0.300	0.282	0.029	0.689
Corn_silage	1.000	0.000	0.000	1.000	0.000	0.000	1.000	0.000	0.000
Cotton	0.938	0.052	0.009	0.497	0.098	0.404	0.000	0.132	0.868
Dates	0.102	0.128	0.770	0.000	0.180	0.820	0.000	0.179	0.821
Figs	0.102	0.128	0.770	0.007	0.175	0.819	0.000	0.172	0.828

Crop	2000			2020			2060		
	Flooding	Sprinkler	Dripping (surface/ subsurface)	Flooding	Sprinkler	Dripping (surface/ subsurface)	Flooding	Sprinkler	Dripping (surface/ subsurface)
Fruit_other	0.343	0.316	0.341	0.288	0.230	0.482	0.148	0.026	0.825
Garlic	0.437	0.563	0.001	0.000	0.185	0.815	0.000	0.000	1.000
Grapes	0.232	0.091	0.676	0.187	0.000	0.813	0.000	0.000	1.000
Lemons	0.102	0.128	0.770	0.007	0.175	0.819	0.000	0.172	0.828
Lettuce	0.380	0.372	0.248	0.111	0.433	0.455	0.000	0.419	0.581
Melons	0.508	0.212	0.280	0.541	0.000	0.459	0.000	0.000	1.000
Non_legume_hay	0.856	0.125	0.019	0.518	0.174	0.309	0.015	0.284	0.701
Nuts_other	0.343	0.316	0.341	0.288	0.230	0.482	0.148	0.026	0.825
Oats	0.874	0.106	0.020	0.698	0.159	0.143	0.445	0.227	0.329
Olives	0.102	0.128	0.770	0.007	0.175	0.819	0.000	0.172	0.828
Onions	0.437	0.563	0.001	0.000	0.185	0.815	0.000	0.000	1.000
Pasture	0.758	0.194	0.049	0.612	0.315	0.072	0.338	0.576	0.086
Peach	0.343	0.316	0.341	0.288	0.230	0.482	0.148	0.026	0.825
Pears	0.343	0.316	0.341	0.288	0.230	0.482	0.148	0.026	0.825
Peppers	0.380	0.372	0.248	0.111	0.433	0.455	0.000	0.419	0.581
Pistachios	0.192	0.113	0.695	0.068	0.171	0.761	0.000	0.226	0.774
Plums	0.343	0.316	0.341	0.288	0.230	0.482	0.148	0.026	0.825
Potatoes	0.012	0.912	0.076	0.029	0.699	0.272	0.051	0.416	0.533
Prunes	0.343	0.316	0.341	0.288	0.230	0.482	0.148	0.026	0.825
Rice	1.000	0.000	0.000	1.000	0.000	0.000	1.000	0.000	0.000
Safflowers	0.576	0.278	0.146	0.447	0.553	0.000	0.231	0.769	0.000
Sorghum	0.856	0.125	0.019	0.518	0.174	0.309	0.015	0.284	0.701
Spinach	0.380	0.372	0.248	0.111	0.433	0.455	0.000	0.419	0.581
Squash	0.463	0.242	0.295	0.541	0.000	0.459	0.378	0.000	0.622
Sunflowers	0.856	0.125	0.019	0.518	0.174	0.309	0.015	0.284	0.701
Sweet_potatoes	0.012	0.912	0.076	0.029	0.699	0.272	0.051	0.416	0.533

Crop	2000			2020			2060		
	Flooding	Sprinkler	Dripping (surface/ subsurface)	Flooding	Sprinkler	Dripping (surface/ subsurface)	Flooding	Sprinkler	Dripping (surface/ subsurface)
Tomatoes	0.666	0.278	0.024	0.000	0.000	1.000	0.000	0.000	1.000
Vegetables_other	0.380	0.372	0.248	0.111	0.433	0.455	0.000	0.419	0.581
Wheat_spring	0.874	0.106	0.020	0.698	0.159	0.143	0.445	0.227	0.329
Wheat_winter	0.874	0.106	0.020	0.698	0.159	0.143	0.445	0.227	0.329

Table 9. Manure and fertilizer nitrogen application to corn silage in different counties of California based on Burger and Horwath (2013).

County	Area[a], ha	Manure[b], kgN	Fertilizer[b], kgN
Butte	244	105920	46710
Contra Costa	38	16701	7365
Fresno	10963	4765587	2101594
Glenn	1986	863400	380754
Humboldt	372	161668	71294
Imperial	675	293605	129478
Kern	10688	4645964	2048841
Kings	15744	6844045	3018181
Madera	7267	3158939	1393072
Marin	13	5620	2478
Merced	33601	14606376	6441321
Placer	17	7530	3321
Riverside	183	79583	35095
Sacramento	2962	1287535	567795
San Bernardino	945	410766	181145
San Joaquin	17816	7744563	3415304
San Luis Obispo	21	9148	4034
San Mateo	1	528	233
Santa Barbara	304	131938	58184
Sonoma	437	189990	83784
Stanislaus	19608	8523523	3758821
Sutter	263	114456	50475
Tehama	211	91653	40418
Tulare	38941	16927599	7464966
Yolo	191	83033	36617
Yuba	87	37856	16694
Grand Total	163578	71107525	31357977

b. Area listed is for 2017.

c. Nitrogen application rate for manure is 434.7 kgN ha^{-1} and for fertilizer is 191.7 kgN ha^{-1}.

Simulation of Soil NO_X Emissions

The simulation of soil NO_X emissions was performed by linking the DNDC model with the California-specific database containing spatial and temporal information on meteorology, crop, soil, and land management practices. For each given year, the model was run for three consecutive years. The simulation for the first two years was to initialize the model, allowing carbon and nitrogen speciation in soil to match closely to field conditions. The results of the third year were used to be the emission estimates. For example, for CEIDARS, the simulation of soil NO_X emissions was performed for 2015, 2016 and 2017, and the 2017 results were reported as the CEIDARS inventory.

NO_X emissions for cropland were simulated under the four irrigation methods used in California (flooding, sprinkler, drip, and subsurface drip) separately. For each irrigation method, 3190 individual simulations were conducted with unique weather, soil properties, cropping system, and management practices (modeling units). The NO_X emissions under the actual irrigation practices for each crop were then calculated by weighting the emissions obtained for each of the individual irrigation methods using their fractions for a given crop. The statewide total soil NO_X emissions from cropland were the weighted sum of all the modeling units.

Modeling of soil NO_X emissions for CEPAM were performed every fifth or tenth year (i.e., 2000, 2005, 2009, 2015, 2020, 2030, 2040, 2050, and 2060), and emission estimates for other years were then interpolated from the modeled years. 2009, instead of 2010, was chosen because 2010 had an especially low cropland acreage (17% below both 2009 and 2011), resulting in an abrupt drop of soil NO_X emissions, and therefore is not considered suitable as a base year for interpolation.

Model Validation

The DNDC model used in our methodology had been calibrated and validated in a prior project with extensive N_2O measurements in cropland and was found to perform well with an r^2 of 0.92 and a p-value of <0.001 (Deng et al., 2018a; 2018b), indicating that the model adequately represented the biophysical conditions of agro-ecosystems in California. There was a much smaller dataset for NO_X emissions than for N_2O, which was collected from major California's cropping systems over the past decade. Because NO_X and N_2O are related N gases arising from the same set of biogeochemical processes, no further calibration of the model was deemed necessary. However, to evaluate the model performance, an independent comparison was made between the model predictions and the observed NO_X data using only field measurements in California that had relatively longer sampling period and higher frequency and thus allowed an estimate for seasonal emissions. Figure 3 shows the comparison of the model predictions and field observations from 15 datasets collected from California cropping systems. Overall, the model predicted the measured soil NO_X emissions closely, with an r^2 of 0.69 and a p-value of <0.001, demonstrating again that the model is capable of reasonably simulating N speciation and emissions from California agricultural ecosystems. However, with a regression coefficient of 1.11, on average, the model underestimated field emissions roughly by 11%.

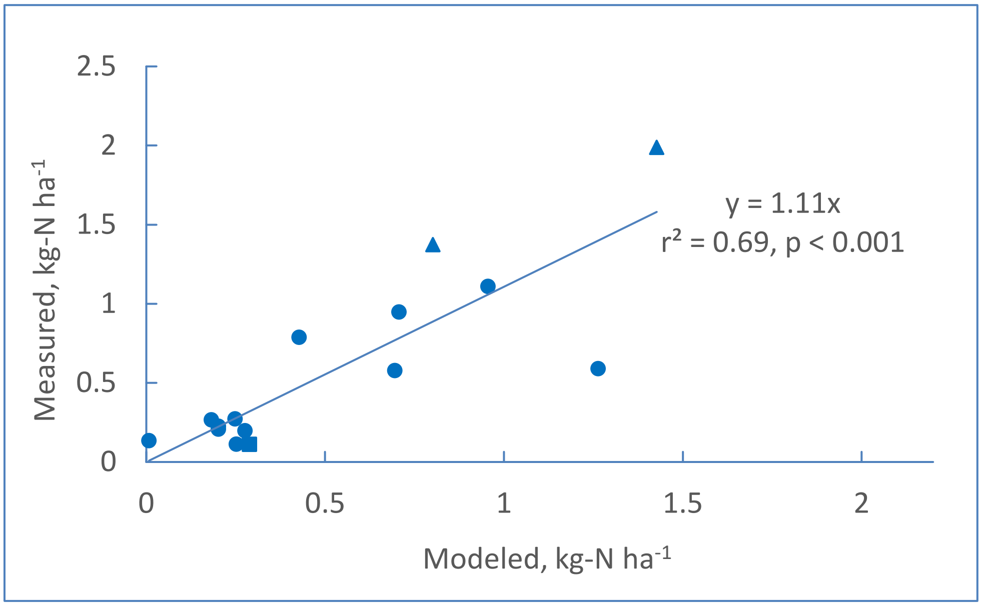

Figure 3. Comparison of DNDC model predictions and field measurements of soil NO_X emissions from California cropping systems. Field data were obtained from Matson et al. (1997) (■), Burger and Horwath (2013) (●), and Oikawa et al. (2015) (▲).

EMISSION ESTIMATES

The soil NO_X emissions estimates of different land use categories for CEIDARS (2017) are summarized in Table 10. Detailed estimates by air basin, air district, and county are provided in Appendix A. The simulated amount of total soil NO_X emissions in California was 8,919 MT (or 9831 short ton) as NO_2 in 2017, driven principally by fertilizer nitrogen use. Cropland, which received over 90% of the State's fertilizer nitrogen applications, was the dominant source of soil NO_X emissions, contributing over 54% (4845 MT) of the statewide total emissions. Developed land, with its intensive turf grass management, contributed 2,451 MT NO_X emissions (28%), followed by forest which contributed 661 MT (7.4%). Shrub land (4.7%) and grassland (4.6%) contributed roughly equal amounts of NO_X emissions, at around 413 MT. Fallow land emitted the least (1.5%) of the statewide soil NO_X emissions. Combined, the emission rate of soil NO_X from all land use covers was 24 MT day^{-1} statewide, with 8.7 MT day^{-1} in the SJV. These estimates may be underestimated by the DNDC model as indicated by the model validation against observed data (Figure 3).

Soil NO_X emissions from 2000 to 2060 besides 2017 are displayed in Figure 4. Overall, the total soil NO_X emissions showed a decreasing trend over the past 20 years or so with the total amount dropped 5.2% from 9593 MT in 2000 to 9097 MT in 2020. Total emissions, however, are predicted to increase slightly in next 40 years (3.4%), primarily from developed land due to the continued urban expansion per CDOF population forecast which predicted the State's population to grow by 11% by 2060 (CDOF, 2021).

Please note that the above emission forecasts did not consider impacts of potential climate change as they were obtained using the average meteorology of the last ten years. The emission forecasts may need to be updated in the future when new meteorology and land use data become available or their predicted trends (such as Figure 2) deviate significantly from the assumptions adopted in the current model.

Table 10. Summary of fertilizer use and NO_X emissions by land use covers in California for 2017.

Land use category	Area		Fertilizer use		NO_X emission	
	ha	%	N, MT	%	MT	%
Cropland	3943064	9.6	533047	90.4	4845	54.3
Urban	2729992	6.7	37945	6.4	2451	27.5
Forest	9435771	23.0	0	0	661	7.4
Grassland	4501232	11.0	18532	3.1	410	4.6
Shrub Land	17703075	43.2	0	0	416	4.7
Fallow	1882887	4.6	0	0	137	1.5
Excluded	754671	1.8	0	0	0	0
Grand Total	40950691	100	589524	100	8919	100

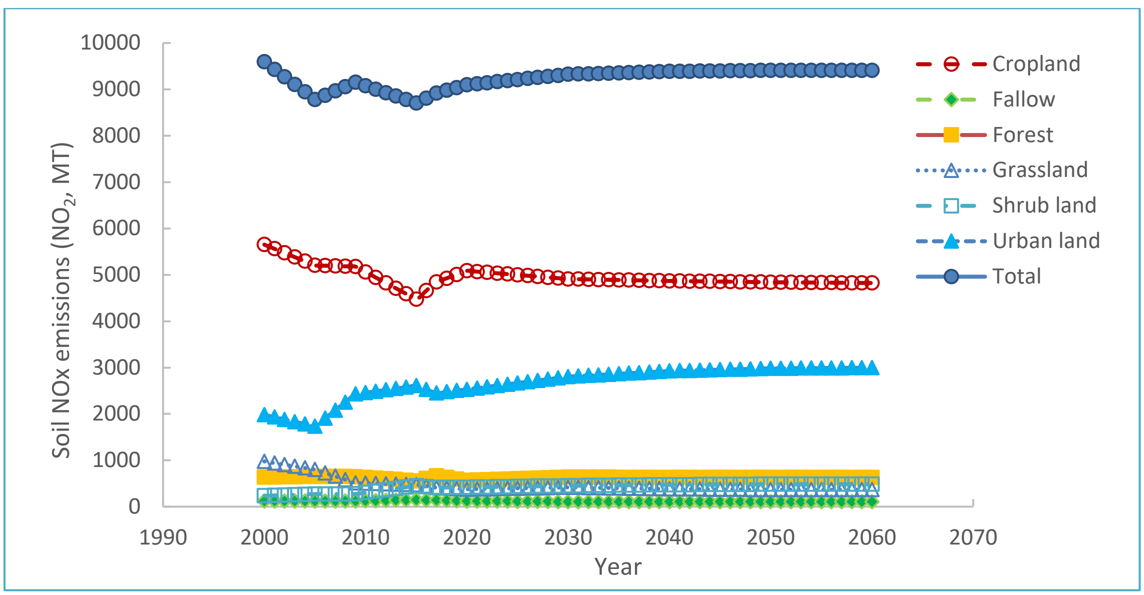

Figure 4. Soil NO_X emissions (NO_2, MT) estimated by the DNDC modeling from 2000 to 2060.

EMISSION ESTIMATE UNCERTAINTIES

To evaluate uncertainties in our model estimates, two separate sensitivity analyses of soil NO_X emissions were performed for the two largest sources of cropland and developed land. The sensitivity analysis for cropland was performed to assess the uncertainties associated with the variability of model inputs in soil properties, irrigation methods, and fertilizer type (NO_3^- vs. NH_4^+) used in cropland. The approach of ''Most Sensitive Factor'' was adopted to estimate the range of potential emissions due to variability of the most sensitive soil property (Li et al., 1996). SOC was chosen to be the most sensitive soil parameter as it acts as a substrate in both nitrification and denitrification, the two fundamental reactions producing NO_X. The minimum and maximum SOC values in the SSURGO database were used in the model to bracket the likely outcomes of NO_X emissions as a result of soil property variability. Soil clay content is also a critical parameter, especially in determining soil hydraulic properties such as field capacity and water filled pore space (WFPS). The WFPS has been used as a sole determinant in regulating gaseous N species (NO_X, N_2O and N_2) emitting from soil in previous studies (Wang et al., 2017; Almaraz et al., 2018). The effects of WFPS on NO_X emissions, however, were evaluated by varying irrigation methods that would apply different depths of water to soil and thus control the WFPS directly. Finally, NO_3- and NH_4-N are the two basic forms of fertilizer N that impact nitrification and denitrification differently. As mentioned earlier, NH_4-N is a more efficient form to produce NO_X than NO_3-N.

Table 11 summarizes the results of the uncertainty analysis for cropland. Since the uncertainty analysis focused on relative changes of emissions, the DNDC model was run using the crop acreage data from the 2012 USDA's Census of Agriculture (USDA, 2000-2020). As Table 11 shows, among the three variables analyzed, the largest uncertainty of soil NO_X emissions from cropland was associated with the type of fertilizer N applied. The estimated emissions changed between 53% (with NO_3-N) to 121% (with NH_4-N) of the baseline emissions with a net difference of 68% between the two N forms, compared to the net difference of 18% for varying SOC and 16% for varying irrigation methods. Using NO_3-N based fertilizers would cut baseline cropland emissions by 47% as the NO_3-N would limit nitrification, the principal process that produces NO_X, in soil. No sensitivity analyses were performed for meteorological variables, soil textures, and other management practices, which also affect emissions but the uncertainties they would pose on soil NO_X emissions are deemed smaller compared to the three selected variables shown in Table 11.

Table 11. Summary of uncertainty analyses on NO_X emissions from cropland.

Variable	Value	NO_2, MT	% Baseline
SOC	SOC min (average=0.67%)	5207	94%
	SOC max (average=1.69%)	6195	112%

Variable	Value	NO_2, MT	% Baseline
Fertilizer type	NO_3-N	2933	53%
	NH_4^+-N	6697	121%
Irrigation method	Flooding (average=98 cm)	5522	100%
	Sprinkler (average=80 cm)	5836	105%
	Surface drip (average=68 cm)	5609	101%
	Subsurface drip (average=61 cm)	4918	89%
Baseline	SOC average=1.19% and management practices vary by crop	5544	100%

Our model only accounted for soil NO_X emissions from turf grass in developed land. The difficulty in estimating turf grass area is another factor of significant uncertainty in our emission estimates. The model assumed the fraction of turf grass in developed land to be 0.05, 0.08, 0.12 and 0.10 for high-, low-, medium-density, and open space, respectively, which resulted in a total turf grass area of 261,526 ha statewide based on an analysis using 2012 CDL, equivalent to 9.7% of the total developed land. Milesi et al. (2005) estimated turf grass area in California to be 1.1 million ha, which is equal to 41% of the total developed land of the 2012 CDL. If 41% is taken as the upper limit of turf grass fraction, soil NO_X emissions from developed land would increase from the current estimate of 2,451 MT to 10,465 MT. If the lower limit of turf grass area is assumed to be half of the current fraction (i.e., 5% of developed land as turf grass), the turf grass emissions would be reduced to 1,225 MT. The fractions assumed in the model represented "best guesses" based on an inspection of Google satellite maps and the predicted water usage consistent with the statewide water budget for urban use (NRDC, 2014).

Using the above uncertainty bounds, it is estimated that in 2017, California statewide soil NO_X emissions could range from 5,412 MT to 17,941 MT (as NO_2), with the most likely estimate being around 8,919 MT, which was the baseline emissions calculated using representative SOC values for cropland and the default activities database built on the best information available for 2017.

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APPENDIX A

Monthly Emissions of Soil NO_X for CEIDARS (2017) from Different Air Basins, Air Districts, and Counties in California

Table A1. Soil NO_X emission estimates (short ton) by air basin in California for 2017.

Air basin	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Great Basin Valleys	10.93	9.53	8.44	7.12	7.05	4.94	6.07	11.65	12.15	12.19	10.54	8.03
Lake County	1.81	1.10	2.30	2.47	3.89	5.88	4.54	7.19	4.67	7.73	2.69	3.68
Lake Tahoe	0.68	0.48	0.86	0.81	0.77	0.69	0.60	1.19	0.78	1.11	0.73	0.97
Mojave Desert	17.50	18.80	22.86	19.57	13.29	12.92	14.90	19.70	18.02	22.11	17.89	18.09
Mountain Counties	32.41	24.71	35.71	35.74	37.53	30.23	33.16	40.38	26.22	33.17	34.22	35.52
North Central Coast	18.05	18.96	25.57	23.51	22.88	38.45	39.07	47.56	29.02	39.26	20.42	18.07
North Coast	47.20	34.73	50.83	51.58	60.78	74.18	69.82	88.69	63.98	82.72	62.97	59.26
Northeast Plateau	14.77	9.55	17.43	20.07	38.52	54.28	60.45	37.10	19.19	16.25	23.15	17.11
Sacramento Valley	42.09	58.93	111.59	147.25	367.99	254.77	220.52	190.42	107.56	107.39	93.98	67.92
Salton Sea	16.01	50.19	70.46	47.92	20.82	31.74	28.92	17.33	17.68	21.38	17.48	19.12
San Diego County	5.63	3.54	11.27	19.66	14.89	27.34	18.95	30.19	22.84	40.27	23.04	33.32
San Francisco Bay Area	17.73	18.02	43.57	58.51	61.94	104.71	89.65	121.25	70.92	114.43	49.44	50.32
San Joaquin Valley	77.96	142.87	231.49	264.78	497.03	585.96	638.90	400.01	177.41	180.48	243.11	130.94
South Central Coast	27.47	24.05	30.09	28.37	25.81	47.80	54.63	57.09	39.68	51.47	25.17	27.77
South Coast	8.89	9.55	20.98	34.62	26.77	43.54	36.61	62.18	40.93	59.88	47.79	51.83
Grand Total	339.1	425.0	683.4	762.0	1200.0	1317.4	1316.8	1131.9	651.1	789.9	672.6	541.9

Table A2. Soil NO_X emission estimates (short ton) by air district in California for 2017.

Air district	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Amador	1.67	1.38	2.45	2.36	1.97	2.82	2.78	2.29	1.51	1.90	2.07	2.13
Antelope Valley	1.11	1.47	2.31	2.64	2.46	3.33	2.67	3.55	2.75	3.91	2.29	2.57
Bay Area	17.73	18.02	43.57	58.51	61.94	104.71	89.65	121.25	70.92	114.43	49.44	50.32
Butte	3.59	4.11	8.80	14.57	65.33	40.59	42.73	30.90	14.87	12.62	7.21	6.48
Calaveras	1.67	1.23	2.35	2.21	1.76	1.41	1.48	1.83	1.26	2.08	1.92	2.78
Colusa	3.80	4.88	6.23	15.36	79.03	24.12	15.93	19.67	7.88	5.62	5.83	3.70
El Dorado	4.98	3.06	6.15	5.86	5.94	4.19	3.96	6.85	4.19	6.22	4.83	6.51
Feather River	4.77	6.54	12.23	20.05	60.27	29.31	27.96	16.49	10.15	8.13	7.52	5.31
Glenn	3.66	5.12	8.37	15.32	44.27	31.05	28.01	23.74	10.76	7.19	6.00	3.64
Great Basin Unified	10.93	9.53	8.44	7.12	7.05	4.94	6.07	11.65	12.15	12.19	10.54	8.03
Imperial	14.65	48.80	69.00	46.00	19.15	29.44	26.05	14.07	14.14	17.25	14.47	16.02
Kern	0.51	1.92	1.74	1.38	0.80	0.94	1.79	1.81	1.16	1.76	1.03	1.04
Lake	1.81	1.10	2.30	2.47	3.89	5.88	4.54	7.19	4.67	7.73	2.69	3.68
Lassen	1.60	1.81	2.31	2.18	5.76	7.04	7.72	6.18	3.75	3.06	5.08	2.70
Mariposa	5.33	3.94	5.46	5.34	4.47	4.98	6.51	7.10	4.08	4.44	4.44	4.39
Mendocino	12.16	7.71	15.10	14.35	18.81	22.37	25.75	31.33	18.56	26.48	15.18	16.70
Modoc	3.99	2.44	5.68	6.78	10.83	17.79	22.49	9.93	7.99	3.74	5.67	3.57
Mojave Desert	15.07	15.01	18.35	15.22	9.67	8.17	9.85	13.61	13.15	15.46	13.63	13.55
Monterey Bay Unified	18.05	18.96	25.57	23.51	22.88	38.45	39.07	47.56	29.02	39.26	20.42	18.07
North Coast Unified	31.46	25.09	32.02	33.37	38.14	46.01	36.62	48.92	40.76	47.72	42.13	38.36
Northern Sierra	5.54	4.50	6.22	7.83	14.38	10.10	10.71	13.42	8.72	10.48	9.41	8.48

Air district	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Northern Sonoma	3.58	1.92	3.72	3.86	3.83	5.80	7.44	8.43	4.66	8.52	5.66	4.20
Placer	4.23	3.67	6.85	6.92	7.49	5.75	7.72	7.50	5.62	7.25	5.97	6.46
Sacramento Metro	6.15	6.70	16.56	18.17	30.32	41.08	32.63	28.18	20.70	25.84	17.05	11.24
San Diego	5.63	3.54	11.27	19.66	14.89	27.34	18.95	30.19	22.84	40.27	23.04	33.32
San Joaquin Valley Unified	77.96	142.87	231.49	264.78	497.03	585.96	638.90	400.01	177.41	180.48	243.11	130.94
San Luis Obispo	11.54	9.53	13.39	13.60	12.75	24.30	29.76	29.38	16.51	22.58	9.43	10.42
Santa Barbara	9.73	8.06	9.23	8.28	8.14	14.76	15.68	16.11	14.38	18.27	9.64	10.31
Shasta	1.24	1.60	2.15	2.22	8.30	13.45	10.81	16.04	8.65	13.68	8.49	10.22
Siskiyou	9.18	5.30	9.44	11.11	21.92	29.44	30.23	20.99	7.44	9.45	12.41	10.84
South Coast	11.04	11.35	22.88	36.88	28.80	46.33	40.07	66.17	45.44	64.99	51.76	55.87
Tehama	4.42	4.61	8.56	8.96	10.36	18.45	20.17	16.19	10.98	10.75	6.34	6.35
Tuolumne	10.85	8.42	9.88	9.87	7.79	6.78	7.72	8.93	6.38	7.64	9.96	8.64
Ventura	6.21	6.46	7.47	6.49	4.93	8.74	9.19	11.60	8.79	10.62	6.10	7.05
Yolo-Solano	13.28	24.37	45.88	48.74	64.60	51.62	35.15	32.85	18.83	17.83	31.89	18.06
Grand Total	339.1	425.0	683.4	762.0	1200.0	1317.4	1316.8	1131.9	651.1	789.9	672.6	541.9

Table A3. Soil NO_X emission estimates (short ton) by county in California for 2017.

County	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Alameda	1.62	1.91	5.23	7.10	6.73	12.06	10.26	14.46	8.15	12.20	4.87	5.11
Alpine	1.13	0.48	1.03	1.15	1.63	0.71	0.98	1.07	0.82	0.68	0.99	1.00
Amador	1.67	1.38	2.45	2.36	1.97	2.82	2.78	2.29	1.51	1.90	2.07	2.13

County	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Butte	3.59	4.11	8.80	14.57	65.33	40.59	42.73	30.90	14.87	12.62	7.21	6.48
Calaveras	1.67	1.23	2.35	2.21	1.76	1.41	1.48	1.83	1.26	2.08	1.92	2.78
Colusa	3.80	4.88	6.23	15.36	79.03	24.12	15.93	19.67	7.88	5.62	5.83	3.70
Contra Costa	2.54	3.78	9.83	12.07	14.40	16.77	11.39	15.36	8.58	11.38	9.02	6.87
Del Norte	7.82	7.42	8.73	9.45	8.36	11.93	11.69	14.64	12.63	14.97	14.86	10.59
El Dorado	4.98	3.06	6.15	5.86	5.94	4.19	3.96	6.85	4.19	6.22	4.83	6.51
Fresno	15.27	31.07	41.92	51.30	98.07	89.32	93.69	78.37	36.73	41.90	55.94	37.75
Glenn	3.66	5.12	8.37	15.32	44.27	31.05	28.01	23.74	10.76	7.19	6.00	3.64
Humboldt	17.84	14.87	17.07	17.59	19.47	26.32	19.76	24.71	23.04	23.50	22.09	20.65
Imperial	14.65	48.80	69.00	46.00	19.15	29.44	26.05	14.07	14.14	17.25	14.47	16.02
Inyo	8.31	7.78	5.89	4.42	2.51	2.41	3.34	7.03	9.63	10.05	7.90	5.18
Kern	10.86	18.33	30.65	38.11	54.96	64.31	68.62	55.48	25.33	25.12	26.59	17.57
Kings	4.80	9.32	21.57	26.33	63.32	60.73	69.19	28.16	15.19	12.63	30.26	17.57
Lake	1.81	1.10	2.30	2.47	3.89	5.88	4.54	7.19	4.67	7.73	2.69	3.68
Lassen	1.60	1.81	2.31	2.18	5.76	7.04	7.72	6.18	3.75	3.06	5.08	2.70
Los Angeles	4.19	3.86	10.13	16.32	14.04	21.98	16.60	28.34	20.56	31.66	17.79	20.51
Madera	3.52	8.02	10.62	11.71	22.09	36.53	35.23	39.55	13.24	13.87	10.37	5.75
Marin	0.98	0.76	1.59	1.92	2.19	3.54	4.35	5.07	3.34	6.42	2.29	1.91
Mariposa	5.33	3.94	5.46	5.34	4.47	4.98	6.51	7.10	4.08	4.44	4.44	4.39
Mendocino	12.16	7.71	15.10	14.35	18.81	22.37	25.75	31.33	18.56	26.48	15.18	16.70
Merced	9.03	15.58	26.83	37.23	75.95	79.40	88.46	46.03	19.66	22.08	50.36	16.97
Modoc	3.99	2.44	5.68	6.78	10.83	17.79	22.49	9.93	7.99	3.74	5.67	3.57
Mono	1.49	1.27	1.53	1.55	2.91	1.82	1.75	3.55	1.71	1.46	1.65	1.85
Monterey	13.85	14.20	18.35	16.73	16.18	27.01	28.75	35.02	20.57	27.55	14.57	12.60

County	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Napa	3.62	2.66	3.25	3.93	3.93	6.55	6.33	9.55	4.82	8.65	4.34	3.01
Nevada	2.72	2.81	3.65	4.69	4.32	5.40	5.18	7.37	4.93	5.90	4.33	3.99
Orange	2.79	1.81	5.77	10.40	8.69	16.41	13.07	25.46	13.99	19.22	11.06	15.40
Placer	4.23	3.67	6.85	6.92	7.49	5.75	7.72	7.50	5.62	7.25	5.97	6.46
Plumas	1.41	1.24	1.87	1.63	7.81	3.93	3.57	4.62	2.88	3.51	3.78	3.20
Riverside	6.28	13.32	19.58	19.86	11.37	10.43	11.89	12.33	11.96	13.81	23.18	19.93
Sacramento	6.15	6.70	16.56	18.17	30.32	41.08	32.63	28.18	20.70	25.84	17.05	11.24
San Benito	2.68	3.33	4.54	3.79	3.63	5.27	5.75	5.92	3.02	4.31	2.85	2.65
San Bernardino	13.98	8.84	8.07	8.15	6.83	9.01	11.04	17.20	14.82	19.67	15.64	16.15
San Diego	5.63	3.54	11.27	19.66	14.89	27.34	18.95	30.19	22.84	40.27	23.04	33.32
San Francisco	0.15	0.10	0.60	1.18	1.66	3.26	2.69	3.87	2.70	4.62	1.35	1.67
San Joaquin	16.85	22.68	41.38	42.52	66.34	88.88	91.68	53.82	24.66	28.73	32.47	12.53
San Luis Obispo	11.54	9.53	13.39	13.60	12.75	24.30	29.76	29.38	16.51	22.58	9.43	10.42
San Mateo	1.63	2.12	4.26	6.11	5.32	10.02	7.14	10.20	5.71	11.39	6.36	9.10
Santa Barbara	9.73	8.06	9.23	8.28	8.14	14.76	15.68	16.11	14.38	18.27	9.64	10.31
Santa Clara	4.06	4.21	11.75	16.21	17.28	33.22	26.67	38.41	23.23	34.41	11.36	14.13
Santa Cruz	1.52	1.43	2.68	2.99	3.08	6.17	4.57	6.61	5.43	7.40	3.00	2.82
Shasta	1.24	1.60	2.15	2.22	8.30	13.45	10.81	16.04	8.65	13.68	8.49	10.22
Sierra	1.41	0.46	0.70	1.51	2.25	0.76	1.96	1.43	0.91	1.08	1.30	1.30
Siskiyou	9.18	5.30	9.44	11.11	21.92	29.44	30.23	20.99	7.44	9.45	12.41	10.84
Solano	5.10	11.83	25.06	27.24	28.26	26.02	18.56	18.20	11.13	11.48	13.28	10.66
Sonoma	5.72	3.08	7.91	9.33	10.52	19.25	22.70	25.97	14.99	28.58	11.62	9.19
Stanislaus	5.37	7.59	15.15	16.97	33.17	60.57	57.26	45.23	19.07	17.06	12.98	6.20
Sutter	2.70	3.99	7.85	13.11	43.57	20.07	17.80	9.75	5.53	4.16	4.92	2.83

County	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Tehama	4.42	4.61	8.56	8.96	10.36	18.45	20.17	16.19	10.98	10.75	6.34	6.35
Trinity	5.80	2.80	6.22	6.34	10.32	7.76	5.17	9.57	5.10	9.25	5.19	7.12
Tulare	12.77	32.21	45.12	42.00	83.93	107.18	136.55	55.17	24.69	20.85	25.16	17.63
Tuolumne	10.85	8.42	9.88	9.87	7.79	6.78	7.72	8.93	6.38	7.64	9.96	8.64
Ventura	6.21	6.46	7.47	6.49	4.93	8.74	9.19	11.60	8.79	10.62	6.10	7.05
Yolo	9.16	13.85	23.69	26.02	40.07	31.43	22.13	21.46	11.76	11.65	22.49	10.94
Yuba	2.07	2.55	4.39	6.94	16.70	9.24	10.16	6.73	4.62	3.97	2.60	2.48
Grand Total	339.1	425.0	683.4	762.0	1200.0	1317.4	1316.8	1131.9	651.1	789.9	672.6	541.9