

Chapter 5: Ecosystem services and human well-being

Authors: VR Haden, D Liptzin, TS Rosenstock, J VanDerslice, S Brodt, BL Yeo, R Dahlgren, K Scow,

J Riddell, G Feenstra, A Oliver, K Thomas, D Kanter, TP Tomich

Section 5.4: Climate regulation

Contents:

Main messages

5.4 Climate regulation

5.4.0 Introduction

5.4.1 Measures of radiative forcing and global climate change

5.4.2 Effects of reactive N on the global climate

5.4.3 Effects of reactive N on N₂O emissions

5.4.4 Effects of reactive N on biosphere C stocks and the efflux of CO₂ and CH₄

5.4.5 Effects of reactive N on atmospheric gases and aerosols

5.4.6 Future research needs in California

Boxes:

5.4.1 Nitrous oxide: a greenhouse gas and an ozone depleting substance

5.4.2 Climate impacts of fertilizer manufacture

Figures:

- 21 5.4.1 Potential mechanisms regulating the terrestrial ecosystem responses of CO₂, CH₄ and N₂O
22 production and consumption to increased availability of reactive N
- 23 5.4.2 Types of uncertainty in nitrogen's impact on global climate regulation.
- 24 5.4.3 Influence of anthropogenic reactive N on global radiative forcing on the present climate
- 25 5.4.4 The climate change impacts of US reactive nitrogen emissions from combustion and agriculture,
26 in common units of equivalent Tg of CO₂ (Tg CO₂e) on a 20-year and 100-year global
27 temperature potential (GTP) basis
- 28 5.4.5 Global mean radiative forcings (RF) and their 90% confidence intervals in 2007 for various agents
29 and mechanisms (a) and probability distribution of the global mean combined radiative forcing
30 from all anthropogenic agents shown in (b)
- 31 5.4.6 Global annual emissions of anthropogenic GHGs from 1970 to 2004 (a). Share of different
32 anthropogenic GHGs in total emissions in 2004 in terms of CO₂-eq (b). Share of different sectors
33 in total anthropogenic GHG emissions in 2004 in terms of CO₂-eq (c). Forestry includes
34 deforestation

35

36 **Tables:**

- 37 5.4.1 Atmospheric lifetimes and global warming potential (GWP) values for CO₂, CH₄, and N₂O
- 38 5.4.2 Processes altered by reactive N that have radiative forcing effects. The size of the short-term
39 (20yr) and long-term (100yr) effect is relative to other processes altered by reactive N
- 40 5.4.3 California greenhouse gases and percent of annual total emitted in 1990, 2000 and 2009
- 41 5.4.4 Estimated emissions of N₂O, NO_x and NH₃ by source and fate in California during 2005

42 5.5.5 Default values and uncertainty range for IPCC emission factors used to calculate direct and
43 indirect N₂O emissions from agricultural soils in the California Greenhouse Gas Emissions
44 Inventory

45

46 **Figures:**

47 5.4.1 Potential mechanisms regulating the terrestrial ecosystem responses of CO₂, CH₄ and N₂O
48 production and consumption to increased availability of reactive N.

49 5.4.2 Types of uncertainty in nitrogen's impact on global climate regulation.

50 5.4.3 Influence of anthropogenic reactive N on global radiative forcing on the present climate

51 5.4.4 The climate change impacts of US reactive nitrogen emissions from combustion and agriculture,
52 in common units of equivalent Tg of CO₂ (Tg CO₂e) on a 20-year and 100-year global
53 temperature potential (GTP) basis.

54 5.5.5 Global mean radiative forcings (RF) and their 90% confidence intervals in 2007 for various agents
55 and mechanisms (a) and probability distribution of the global mean combined radiative forcing
56 from all anthropogenic agents shown in (b).

57 5.4.6 Global annual emissions of anthropogenic GHGs from 1970 to 2004 (a). Share of different
58 anthropogenic GHGs in total emissions in 2004 in terms of CO₂e (b). Share of different sectors in
59 total anthropogenic GHG emissions in 2004 in terms of CO₂e (c).

60

61 **Main Messages**

62 **Human activities that increase reactive N have numerous competing effects on the ecosystem and**

63 **biogeochemical processes that regulate the Earth's climate.** Some processes have net warming effects

64 that exacerbate climate change, while other processes have net cooling effects that partially offset the
65 prevailing trend of a warming climate.

66

67 **Emissions of N₂O have a long term warming effect on global climate change.** As the third most
68 important greenhouse gas behind CO₂ and CH₄, N₂O accounts for approximately 8% of total global and
69 3% of total statewide greenhouse gas emissions. The vast majority of N₂O emissions emitted globally
70 and in California come from agricultural sources (N fertilizers, livestock, N₂-fixing crops), while fossil fuel
71 combustion, sewage treatment and industrial sources are also minor sources.

72

73 **N deposition and fertilization tends to have an overall cooling effect on climate by enhancing**
74 **terrestrial C sequestration in plant biomass and soils.** Increased C sequestration due to N input has
75 been documented for many forest, grassland, wetland and agricultural ecosystems in North America (24
76 - 177 kg C per kg N deposited per year), a trend which has also been observed in California.

77

78 **The formation of O₃ from NO_x has both warming and cooling effects on the earth's climate.** Increased
79 ground-level O₃ has adverse effects on plant photosynthesis and CO₂ uptake, which decrease C
80 sequestration by crops and natural vegetation. While estimates suggest that O₃ decreases plant C
81 sequestration by 14 -23% globally, more research is needed to quantify the extent of this impact in
82 California. In contrast, O₃ can also have a small cooling effect on climate by increasing the concentration
83 of hydroxyl radicals (OH), which in turn reduce the lifetime and overall burden of CH₄ in the
84 atmosphere.

85

86 **Atmospheric aerosols formed from NO_x and NH₃ have a short term cooling effect on climate by**
87 **reflecting and scattering solar radiation and stimulating cloud formation and the albedo effect.** Since
88 the formation of aerosols from NO_x and NH₃ are generally linked to different pollution sources (e.g.,
89 fossil fuel → NO_x, livestock → NH₃), the relative contribution of each pollutant and the chemical
90 composition of resulting aerosols is likely to vary considerably across California's landscape.

91

92 **Estimates suggest that anthropogenic sources of N have a modest net-cooling effect on the Earth's**
93 **climate in the near-term (20 yr), but a net warming effect in the long-term (100 yr) as the prolonged**
94 **effects of N₂O dominate the radiative balance.** It should also be noted that the overall effects of N on
95 the climate are relatively small compared to CO₂ from fossil fuel combustion (8% globally, 3-4% in
96 California).

97

98 **5.4 Climate regulation**

99 **5.4.0 Introduction**

100 Nitrogen plays a well-established role in regulating the Earth's climate. Human activities that increase
101 the amount of reactive N that enters terrestrial and aquatic ecosystems can alter many biogeochemical
102 processes that affect the Earth's climate balance (Figure 5.4.1). Most notably, increases in reactive N can
103 change the emission and uptake of the three important greenhouse gases: carbon dioxide (CO₂),
104 methane (CH₄), and nitrous oxide (N₂O). Emissions of N oxides (NO_x) and NH₃ also have important
105 impacts on climate, since they are chemical precursors to ozone (O₃) and various atmospheric aerosols
106 [Box 5.4.1]. The ecosystem processes and atmospheric feedbacks involving N are complex, and thus the
107 magnitude of their effects on the global climate are often uncertain. In this section, we examine the

108 effects of reactive N on the Earth's climate balance paying particular attention to California's
109 contribution to climate change over time through human activities and ecosystem processes that effect
110 global N and carbon (C) cycles.

111 [\[Figure 5.4.1\]](#)

112 [\[Box 5.4.1\]](#)

113

114 **5.4.1 Measures of the radiative forcing and global climate change**

115 Several important metrics are used to quantify the effects of ecosystem processes that regulate the
116 Earth's climate. The two most commonly used measures are radiative forcing (RF) and global warming
117 potential (GWP). Radiative forcing is a measure of the influence that a factor (e.g., greenhouse gas,
118 atmospheric aerosol) has in changing the balance of energy in the atmospheric system and is expressed
119 in Watts per square meter ($W m^2$) of the Earth's surface. More specifically, the Intergovernmental Panel
120 on Climate Change (IPCC) calculates RF as the change in $W m^2$ relative to preindustrial conditions (i.e.,
121 pre-1750) (IPCC 2007). The amount of heat trapped by a particular gas depends on its absorption of
122 infrared radiation, the absorption wavelength and the atmospheric lifetime of the gas species (IPCC
123 2007). By integrating the RF caused by a 1kg pulse of given gas over a standard time period (20 yr, 100
124 yr, 500 yr) its absolute global warming potential (also expressed in $W m^2$) can be calculated. While the
125 IPCC uses the GWP over a 100yr time period in its policy frameworks, the shorter and longer time
126 frames have also proven useful for detailed modeling studies (IPCC 2001; Shine 2007). Another
127 convention adopted by the IPCC is to express the GWP of a gas relative to an equivalent mass of CO_2
128 (IPCC 2007). As such, CO_2 is standardized to a GWP value of 1 and other gases are expressed in terms of
129 carbon dioxide equivalents (CO_2e) integrated over a 100yr time period. For example, the GWP of one kg
130 of N_2O over 100 years is 298 kg CO_2e (Table 5.4.1; IPCC 2007). Due to its computational simplicity, GWP

131 has been widely adopted by scientists and policy makers working under the IPCC framework. More
132 recent work by Shine et al (2005; 2007) has introduced the global temperature potential (GTP) as an
133 additional measure for consideration by the IPCC. The GTP is calculated as the ratio between the global
134 mean surface temperature change (change in degrees K per kg⁻¹ gas) at a given future time point
135 following a pulse or sustained emission of a gas relative to CO₂ (Shine et al. 2005). Since both GWP and
136 GTP are measures of radiative forcing relative to CO₂, they share many advantages as metrics useful for
137 policy making. The main difference between GWP and GTP is that while the GWP integrates the
138 temperature change over a standard time period (i.e., the contribution of the RF at the beginning and
139 end of the time horizon is exactly equal) the GTP calculates the actual temperature change between the
140 time emitted and a precise future end point (i.e., the RF closer to the end point contributes relatively
141 more) (Shine et al. 2005). While GTP has yet to gain widespread usage by the IPCC, several recent
142 studies by the US Environmental Protection Agency have employed this metric to assess the overall
143 impacts of reactive N species on both short- and long-term changes in climate (Pinder et al. 2012a;
144 Pinder et al. 2012b).

145 [\[Table 5.4.1\]](#)

146

147 **5.4.2 Effects of reactive N on the global climate**

148 It is well-established that while some human activities involving reactive N result in warming effects
149 that can amplify climate change, others lead to cooling effects that minimize or offset the prevailing
150 global warming trend (Figure 5.4.2; Erisman 2011; Pinder 2012a; Pinder 2012b). For example, emissions
151 of N₂O have a strong long-term warming effect due to the atmospheric lifetime of the gas and its high
152 GWP (Table 5.4.2; Parry et al. 2007; Smith et al. 2007). In contrast, sequestration of C by natural
153 vegetation caused by increased N deposition typically has a long-term cooling effect on climate (Table

154 5.4.2). The effects of atmospheric aerosols also tend to cool the climate, but since they only remain in
155 the atmosphere for a short time period (hours-weeks) their effects are limited in duration (Table 5.4.2;
156 Liu and Greaver 2009; Shindell et al. 2009).

157 [\[Figure 5.4.2\]](#)

158 [\[Table 5.4.2\]](#)

159 While there is considerable uncertainty in estimating the magnitude of these countervailing
160 processes, several recent studies have developed methods for quantifying the net effects of reactive N
161 on the global climate (Figure 5.4.2). Principal among these is a study by Erisman et al. (2011) which
162 concluded that reactive N has an overall net cooling effect on RF for the Earth's present climate (-0.24
163 $W m^{-2}$), albeit with a wide uncertainty range (-0.5 to +0.2 $W m^{-2}$) (Figure 5.4.3). Using the same
164 methodology, Butterbach-Bahl et al. (2011) also found a net cooling effect of anthropogenic N from
165 European sources on global RF. In contrast, Pinder et al. (2012a, 2012b) used an alternative method to
166 calculate the change in GTP due to reactive N sources in the United States over time. Consistent with
167 previous work they also found a modest cooling effect of reactive N in the near-term (20 yr) due mostly
168 to the short-lived effects of O_3 and N-derived aerosols, but indicated that warming will likely occur in
169 the longer-term (100 yr) when the prolonged effects of N_2O dominate the radiative balance (Figure
170 5.4.4). However, it should also be noted that the net effects of N on climate are very small compared to
171 CO_2 from fossil fuel combustion. Thus, the modest cooling effect of reactive N in the near-term is
172 thought to provide only a slight offset to the significant warming trend that is driven mostly by global
173 CO_2 emissions (Figure 5.4.5).

174 [\[Figure 5.4.3\]](#)

175 [\[Figure 5.4.4\]](#)

176 [\[Figure 5.4.5\]](#)

177 Thus far, the results of these global and national studies have not been down-scaled or
178 disaggregated for California. However, the convergence of evidence indicates that the climate forcing
179 effects of reactive N in California are likely similar to those observed in the US and Europe. While a full
180 radiative balance for reactive N in California is beyond the scope of this analysis, the following sections
181 summarize the existing data and knowledge on the main N-related processes in California that influence
182 climate change in both the short and long term.

183

184 **5.4.3 Effects of reactive N on N₂O emissions**

185 As indicated above, emissions of N₂O have a long-term warming effect on the global climate that is well-
186 established in the scientific literature (Figure 5.4.2; Ramaswamy et al. 2007). The primary biochemical
187 mechanisms that produce N₂O are nitrification and denitrification, which are mediated by aerobic
188 nitrifying bacteria and anaerobic denitrifying bacteria (Figure 5.4.1). Recent estimates suggest that
189 approximately 57 - 62% of global N₂O emissions come from natural sources (10.5-11 Tg N yr⁻¹), with the
190 remaining 38 - 43% attributed to anthropogenic sources (6.7 - 7.8 Tg N yr⁻¹) (Forster et al. 2007; Syakila
191 and Kroeze 2011). Furthermore, human efforts to fix atmospheric N into usable reactive forms through
192 the Haber-Bosch process and the cultivation of N₂-fixing crops have increased N₂O concentrations in the
193 atmosphere by about 16% relative to pre-industrial times (Forster et al. 2007; Park et al. 2012).
194 Emissions of N₂O come from multiple anthropogenic sources including N fertilizers, N₂-fixing crops,
195 livestock urine and manure, sewage and wastewater, biomass burning, and fossil fuel combustion (Parry
196 et al. 2007; Smith et al. 2007). Terrestrial and aquatic ecosystems are also sources of non-anthropogenic
197 N₂O emissions, but significant losses of N from anthropogenic sources to natural and semi-natural
198 ecosystems (e.g., via NO₃ leaching, NH₃ volatilization, NO_x emissions, N deposition) make it difficult to
199 accurately determine whether a molecule of reactive N originates from natural or human fixation.

200 Globally N₂O accounts for about 8% of total anthropogenic GHG emissions if all are expressed in
201 CO₂e, making it the third most important GHG behind CO₂ (77%) and CH₄ (14%) (Figure 5.4.6; IPCC
202 2007; Smith et al. 2007). In California, a relatively small fraction (3-4 %) of the state's total GHG
203 emissions are attributed to N₂O, and these emissions have remained at a relatively stable level between
204 1990 and 2009 (Table 5.4.3; Figure 5.4.2; CARB 2010). This stable trend for N₂O has also been observed
205 nationally and has been attributed to widespread adoption of catalytic converters in recent decades
206 (which reduce both NO_x and N₂O) and has off-set small increases in N₂O from fertilizer consumption.
207 During the 1990s and 2000s, N₂O emissions on the order of 15 -16 MT CO₂e were emitted in California
208 each year, with 68% of N₂O emissions coming from agriculture (Table 5.4.3; Table 5.4.4). The remaining
209 N₂O emissions in California come from sewage treatment (7%) and fossil fuel combustion in the
210 transportation, energy, and industrial sectors (24%) (Table 5.4.4).

211 [\[Figure 5.4.6\]](#)

212 [\[Table 5.4.3\]](#)

213 [\[Table 5.4.4\]](#)

214

215 ***Emissions of N₂O from California agriculture***

216 Despite N₂O being a small fraction of the state's overall GHG emissions, between 30 and 40% of the
217 emissions attributed to agriculture in California come from N₂O emissions (CARB 2010; Haden et al.
218 2012). California's state-wide estimates for the various agricultural sources of N₂O are based on
219 emissions inventory guidelines developed by the Intergovernmental Panel on Climate Change (IPCC
220 2006). The IPCC's Tier 1 methods use default emission factors (EFs) derived from a "bottom-up"
221 assessment of field experiments covering a wide range of global crops, environments, water
222 management regimes, N sources and nutrient management practices (Bouwman et al. 2002a; Bouwman

2002b; Stehfest & Bouwman 2006). These default EFs calculate emissions using a mean value for the proportion of applied N from synthetic fertilizer, N₂-fixing crops, organic fertilizer, and manure that is directly and indirectly emitted as N₂O (Table 5.4.5). Direct emissions, in this case, refer to those which arise from the soil where the N is applied, whereas indirect emissions are those that occur elsewhere in the environment subsequent to leaching or volatilization losses. Using this approach the EF for direct N₂O emissions from most agricultural soils is 1% of applied N, with an additional 0.35-0.45% of applied N emitted indirectly following leaching and volatilization (IPCC 2006). However, it should be noted that considerable natural variation in N₂O flux measurements across many environmental conditions and cropping systems introduces a high degree of uncertainty in the default EFs. For example, the uncertainty in direct N₂O emissions from agricultural soils ranges from 0.003 – 0.03 kg N₂O – N per kg N applied (Table 5.4.5; See Data Table 21). Increasingly, region-specific EFs derived from local agricultural experiments and activity data (i.e. Tier 2 methods) or more sophisticated process-based biogeochemical models (i.e. Tier 3 methods) are being used to further improve the precision and reduce the uncertainty of N₂O estimates (Haden et al. 2012). The region-specific EF used in the California N Assessment to estimate N₂O emissions from 33 California crop categories is recent example of the former (See Chapter 7, Figure 7.6).

[\[Table 5.4.5\]](#)

In contrast to the “bottom up” emissions inventories that have been used by most national and subnational governments, recent studies by Crutzen et al. (2008), Davidson (2009) and Smith et al. (2012) that employ “top-down” accounting methodologies inclusive of both direct and indirect N₂O emissions, suggest that not all of the N₂O emitted over the lifecycle of a newly fixed reactive N molecule is accounted for in IPCC’s default EFs. It should also be noted that the CO₂, CH₄ and N₂O emitted during the Haber-Bosch process used to manufacture N fertilizers are not included in either the top-down or

246 bottom-up accounting frameworks for agricultural emissions referred to above (Box 5.4.2). In the
247 Crutzen et al. (2008) study, which uses a N budget approach informed by data on the size of global N
248 sources and sinks and the known rate of N₂O accumulation in the atmosphere, approximately 3-5% of
249 newly fixed N is ultimately emitted as N₂O. Building on this approach, Smith et al. (2012) found a good
250 fit between observed atmospheric N₂O concentrations from 1860 to 2000 and estimates of N₂O
251 emissions based on a 4% EF by using estimates of reactive N entering the agricultural cycle that account
252 for both mineralization of soil organic N following land use change and NO_x deposited from the
253 atmosphere. In the approach used by Davidson (2009), they assume that N molecules in the fertilizer
254 used to produce animal feed are later recycled in manure applied to soil. The results of their analysis
255 indicate that approximately 2% of N in manure and 2.5 % of N in fertilizer is eventually converted to
256 N₂O. It is important to note that while these top-down methods indicate 2-3 fold higher N₂O emissions
257 than the IPCC's Tier 1 approach, the contribution of N₂O to California's total GHG emissions (< 5-10%) is
258 still relatively minor compared to CO₂. These recent studies also highlight the fact that while the IPCC
259 default EFs provide a computationally simple way to estimate N₂O emissions, the high degree of
260 uncertainty can restrict the precision of national and regional inventory estimates (Smith et al.2010).

261 In an effort to improve estimates of N₂O emissions from California agriculture, state agencies (e.g.
262 California Energy Commission, California Air Resources Board) have commissioned a number of recent
263 field studies to measure emissions for California cropping systems with goals of 1) calibrating and
264 validating soil biogeochemical models (e.g., DAYCENT Model, Denitrification-Decomposition Model), 2)
265 assessing the impact of alternative agricultural practices (De Gryze et al. 2009; De Gryze et al. 2010;
266 Horwath and Burger 2012; Burger et al. 2005). As a case in point, Horwath and Burger (2012) recently
267 published a report of California-based field studies measuring N₂O emissions in tomato, wheat, alfalfa,
268 and rice cropping systems. They found that cumulative N₂O emissions from furrow-irrigated tomatoes

269 ranged between 0.67 to 4.69 kg N₂O-N ha⁻¹ and had EFs between 0.92 and 2.08% of applied N. In wheat,
270 they obtained EFs ranging from 0.24 to 0.98% of applied N (Horwath and Burger 2012), results that were
271 consistently lower than the well-established 1% IPCC default EF and the 1.21% mean EF derived from 25
272 global wheat studies (Linguist et al 2012). Horwath and Burger (2012) also found that EFs for alfalfa, a N-
273 fixing crop, ranged from 4.5% in a 1 year old stand to 12.06 % in an adjacent 5 year old stand. The
274 annual N₂O emissions measured in rice systems ranged from 0.26 to 0.85 kg N₂O-N ha⁻¹ and EFs
275 between 0.12 and 0.74% and were similar to the mean EF estimated in a recent meta-analysis of 17
276 other rice experiments conducted globally (Horwath and Burger 2012; Linguist et al, 2012). While a few
277 studies have also begun to examine N₂O emissions in California orchards and vineyards, more
278 experimental data are needed to validate biogeochemical models for the state's diverse perennial and
279 annual cropping systems (Steenworth and Balina 2010; Smart et al. 2011; Suddick et al. 2011).

280 [\[Box 5.4.2\]](#)

281

282 ***Emissions of N₂O from sewage treatment, transportation, energy generation, and industry***

283 As with agricultural soils, the N₂O emissions that arise from sewage and wastewater treatment facilities
284 are associated with the breakdown and mineralization of N compounds present in the wastewater and
285 effluent. Again, nitrification and denitrification are the main mechanisms driving N₂O emissions. In
286 general, the N₂O emissions occurring directly within the treatment facilities are relatively small
287 compared to the effluent that is discharged into surface water bodies. Overall, sewage and wastewater
288 treatment account for approximately 7% of California's N₂O emissions (Table 5.4.4). In addition to
289 significant amounts of CO₂, the burning of fossil fuels also produces N₂O and accounts for approximately
290 24% of California's N₂O emissions (Table 5.4.4). In the industrial sector, the production of nitric acid via
291 the oxidation of NH₃ and the application of concentrated nitric acid as an oxidizer for production of

292 various chemicals both result in N₂O emissions. In California, N₂O emissions from nitric acid production
293 in California are small and have declined from 535,000 MT CO₂e in 1990 to less than 200,000 MT of
294 CO₂e in 2008 (CARB 2010). Together, N₂O emissions from wastewater treatment, fossil fuel combustion
295 and nitric acid production amount to less than 1% of California's total anthropogenic GHG emissions,
296 which is dominated mostly by CO₂ and to a lesser extent CH₄ (CARB 2010).

297

298 **5.4.4 Effects of reactive N on biosphere C stocks and the efflux of CO₂ and CH₄**

299 *Effects of N on terrestrial C Sequestration*

300 One of the most prominent cooling effects of reactive N is its stimulation of plant growth in terrestrial
301 ecosystems, which removes CO₂ from the atmosphere and sequesters C in plant biomass (Butterbach-
302 Bahl et al. 2011; Pinder et al. 2012a). It is well-established that the net primary productivity (NPP) of
303 most ecosystems is limited by the availability of N (Figure 5.4.1; LeBauer and Treseder 2008).

304 Consequently, estimates suggest that N deposition in temperate North American forests increases
305 above- and below-ground C stocks by 24 - 177 kg C per kg N deposited per year (Sutton et al. 2008; Liu
306 and Greaver 2009; De Vries et al. 2009; Thomas et al. 2010). While generally lesser in magnitude, N
307 deposition also increases C sequestration in the vegetation of temperate grasslands and wetlands
308 (LeBauer and Treseder 2008).

309 Soils are an even larger sink for carbon, with 2-3 times more C stored in soils than in vegetation
310 globally (White et al. 1999). Most evidence from forest ecosystems suggests that sequestration of C in
311 soil increases with higher rates of N deposition (Fenn et al. 1996). In agroecosystems, the application of
312 N fertilizers and manure can also build soil C stocks (Ladha et al. 2011; Pinder et al. 2012a). The main
313 mechanisms responsible for N-induced C storage in soil are greater inputs of organic matter through leaf

314 litter, crop residues, decreased rates of litter decomposition, and decreased soil respiration (Knorr et al.
315 2005; Janssens et al. 2010).

316 Several studies of California forest ecosystems have found that N deposition contributes to
317 increased C storage in both vegetation and soil organic matter. For example, in Southern California's San
318 Gabriel and San Bernardino Mountains higher rates of N deposition were associated with increased
319 rates of biomass accumulation in over-story trees, leaf litter on the forest floor, and soil organic matter
320 levels (Fenn et al. 1996). Working in the Sierra Nevada Mountains, Powers and Reynolds (1999) found
321 that water is generally the most limiting factor for forest growth, but also documented tree growth
322 responses and C sequestration with increased N inputs. While the above-mentioned studies linking
323 reactive N to increased C storage in California's vegetation and soils are broadly consistent with national
324 and international studies (Pinder et al. 2012a; Pinder 2012b; Erisman et al. 2011), no efforts thus far
325 have been made to quantify the total amount of C sequestered in California due to N deposition and
326 application nor its relative contribution to global climate change.

327 In some cases, excessive N inputs can lead to "N saturation" where the negative effects of soil
328 acidification, base-cation leaching, aluminum toxicity, and Fe immobilization are thought to overwhelm
329 the positive effects of N fertilization, ultimately leading to forest decline and loss of stored C (Aber et al.
330 1989; Matson et al. 2002; Bowman et al. 2008). The adverse effects of excess N are also likely to differ
331 among plant species and ecosystems. Instances of N saturation have been reported in the forests of
332 California's San Bernardino Mountains, though measurable losses of C from forest decline were not
333 observed in this case (Fenn et al. 1996). Furthermore, these authors hypothesize that the high base
334 saturation of arid forest soils in the Western US make decline less likely than in other forest ecosystems
335 (Fenn et al. 2003). While more long-term research is needed to determine if N saturation from
336 continued air pollution will eventually lead to losses of stored C, it is provisionally agreed upon by most

337 that inputs of reactive N generally have a positive effect on C sequestration in California's ecosystems
338 (Figure 5.4.2). That said, it is important to note that plant biomass and soils are not permanent sinks for
339 carbon and a significant fraction of the carbon will eventually be returned to the atmosphere due
340 following plant death, harvest, decomposition, and wild-fire. Future research conducted in California is
341 therefore critically important, not just to understand the N response from different ecosystems and
342 plant species, but also to determine the time-scales of carbon storage and loss to the atmosphere.

343
344 ***Effects of N on CH₄ emissions in terrestrial and wetland ecosystems***

345 In most terrestrial and wetland ecosystems CH₄ production and oxidation by soil microbes occurs
346 concurrently, and the balance of these processes regulates the net flux of CH₄ to the atmosphere
347 (Bodelier and Laanbroek 2004; Liu and Greaver 2009). As discussed above, enrichment of N generally
348 increases the growth of vegetation and the amount of organic matter present in soil. The increased
349 availability and mineralization of organic C subsequently drives greater O₂ consumption and creates a
350 more anaerobic environment in the soil. At the same time, higher levels of NH₄ in soil may also reduce
351 the rate of CH₄ oxidation to CO₂ by methanotrophic bacteria. Together these processes provide more C
352 substrate and more suitable redox conditions for methanogenic bacteria, thus stimulating the net
353 production of CH₄ (Figure 5.4.1; Liu and Greaver 2009).

354 Liu and Greaver (2009) carried out a meta-analysis of existing studies which found that N
355 addition via fertilization and deposition increased in CH₄ production by 95% and decreased CH₄
356 oxidation by 38% when averaged across grassland, wetland and anaerobic agricultural systems.
357 However, when each ecosystem type was analyzed separately the effect of N addition on both CH₄
358 production and CH₄ oxidation was only significant in anaerobic agricultural fields. When combined,
359 these processes result in more total CH₄ entering the atmosphere, albeit only a very small amount more

360 since agricultural soils tend to be weak sinks. Consequently, when Liu and Greaves estimates were used
361 in recent studies the overall warming effect of N on net CH₄ emissions occurring in anaerobic
362 agricultural fields was found to be virtually negligible at both the US national scale (Figure 5.4.4; Pinder
363 et al. 2012) and the global scale (Figure 5.4.5; Erisman et al. 2011). At present, no studies have
364 quantified the overall effect of reactive N on CH₄ emissions in California. However, it is reasonable to
365 assume that the universal biochemical processes that govern CH₄ emissions in soils will yield results in
366 California that are similar to those observed in other wetland, forest, grassland and agricultural
367 ecosystems (Figure 5.4.2).

368

369 **5.4.5 Effects of reactive N on atmospheric gases and aerosols**

370 *Effects of N and O₃ on ecosystems and the atmosphere*

371 As discussed in Chapter 5.3, emissions of NO_x and NH₃ have a multitude of effects on the chemistry of
372 atmospheric gases and the formation of O₃ and aerosols, many of which have important implications for
373 the Earth's climate. Most importantly, NO_x and volatile organic compounds play a role in the formation
374 of tropospheric O₃, which has a warming effect on the climate (Pinder et al. 2012a) through its adverse
375 effects on plant photosynthesis and CO₂ uptake (Felzer et al. 2004; Pan et al. 2009; Arneth et al. 2010;
376 See Chapter 5.3). The damaging effects of tropospheric O₃ on plant growth are estimated to decrease
377 the ability of the world's vegetation to sequester atmospheric CO₂ by as much as 14-23% (Figure 5.4.4;
378 Sitch et al. 2007; Pinder et al. 2012b). While NO_x and O₃ concentrations throughout much of California
379 have been declining since the 1970s (See Figures 5.3.3 and 5.3.6), O₃ levels during the spring and
380 summer months are still among the highest in the United States (Felzer et al. 2004). Experimental and
381 modeling studies indicate that sensitivity to tropospheric O₃ is generally highest for crops followed by
382 deciduous vegetation, with coniferous vegetation generally more tolerant (Felzer et al. 2004; Shrestha

383 and Grantz 2005; Grantz and Shrestha 2006). Recent studies by Felzer et al. (2004, 2005) suggest that in
384 spite of high O₃ levels the overall effect on C storage in Southwestern ecosystems (inclusive of
385 California) is lower than in the Midwestern and Southeastern regions of the United States. This result is
386 due mainly to California's arid summer climate which constrains net primary productivity and thus the
387 total amount of C sequestered by native vegetation. While these studies are inclusive of California, no
388 focused efforts have been made to quantify the impact of O₃ on statewide C sequestration.

389 In the atmosphere O₃ also has a direct warming effect on the climate since it is a short-lived
390 greenhouse gas that effectively traps heat. At the same time, there is a small feedback chemical
391 reactions also involving interactions between O₃ and CH₄ which occur throughout the atmosphere and c
392 have a small cooling effect on the climate (Holmes et al. 2013). This is because increases in O₃ also
393 increase the concentrations of hydroxyl radicals (OH), which in turn reduce the lifetime and overall
394 burden of CH₄ in the atmosphere (Butterbach-Bahl, et al. 2011; Holmes et al. 2013). Since O₃ itself has a
395 short atmospheric lifetime, the cooling effect is very small and more important in the short-term (20 yr)
396 and almost negligible in the long-term (100 yr) (Figure 5.4.4; Pinder et al. 2012a).

397 Overall, the warming associated with the adverse effects of O₃ on vegetation and the direct
398 trapping of heat by O₃ dominate the radiative balance (Shindell et al. 2009; Erisman 2011).
399 Understanding these processes, as well as the small counteracting effects of O₃ on atmospheric CH₄, is
400 an emerging area of research, thus considerable uncertainty remains regarding the net effects of O₃ on
401 the earth's radiative balance and how the effects change over time (Ramaswamy et al. 2007). In
402 California, more studies are needed to quantify the total amount of O₃ formed in the atmosphere,
403 evaluate its competing effects, and assess how strategies to reduce O₃ might impact global climate
404 change.

405

406 *Effects of N on atmospheric aerosols*

407 While the amount of data and level of agreement regarding the direct climate effects of greenhouse
408 gases (CO₂, CH₄, N₂O) is considered to be high among scientists, there remains considerable uncertainty
409 about the effects of atmospheric aerosols on the global climate due in large part to the complexity of
410 the interactions which occur between aerosolized chemicals and clouds (Anderson et al. 2003;
411 Ramaswamy et al. 2007). In this context, aerosols refer to any fine particulate matter or liquid droplet
412 that is suspended in the gaseous environment. The limited evidence that is available on aerosols and
413 particulate matter derived from NO_x and NH₃ emissions are tentatively agreed by most to have a short-
414 term cooling effect on the climate by scattering solar radiation and stimulating cloud formation and the
415 albedo effect (Figure 5.4.2; Shindell et al. 2009; Erisman et al. 2011). The main aerosols formed from
416 chemical reactions with NO_x and NH₃ include: ammonium nitrate (NH₄NO₃), ammonium sulfate
417 (NH₄SO₄), ammonium bisulfate (NH₄(SO₄)₂), calcium nitrate (Ca(NO₃)₂), and sodium nitrate (NaNO₃).
418 Each of these aerosols form under different conditions, and holds differing amounts of water which
419 leads to a range of effective sizes, optical properties, and radiative effects (Butterbach-Bahl, et al. 2011).

420 The chemical complexity of atmospheric aerosols and the paucity of empirical data on their
421 effects results in a high level of uncertainty regarding the magnitude and duration of their impact on the
422 Earth's radiative balance (Figure 5.4.5; Ramaswamy et al. 2007). Globally, aerosols derived from NO_x and
423 NH₃ are together estimated to have a radiative forcing of -0.38 W m², with the negative value indicative
424 of a modest cooling effect on the present climate (Shindell et al. 2009; Erisman et al. 2011). For the US,
425 Pinder et al. (2012a) found a similar cooling effect of N-derived aerosols in the near term (20 yr), but
426 considered their long-term impact on climate to be negligible relative to CO₂, CH₄, and N₂O emissions
427 and terrestrial C sequestration (Figure 5.4.4). Recent studies also suggest that the short term cooling
428 effect of NO_x-derived aerosols are 2 to 4 times as large as the effect of NH₃-derived aerosols (Shindell et

429 al. 2009; Pinder et al., 2012a). However, since the formation of aerosols from NO_x and NH_3 are generally
430 linked to different pollution sources (e.g., fossil fuel \rightarrow NO_x , livestock \rightarrow NH_3) the relative contribution
431 of each pollutant is likely to vary considerably across California's landscape (See Chapter 5.3). For
432 example, recent studies indicate that in the San Joaquin Valley, where fossil fuel combustion and
433 agricultural activities produce a balanced mix of NO_x and NH_3 , NH_4NO_3 tends to be the most abundant
434 chemical species among atmospheric aerosols (Battye et al. 2003). In parts of California where NH_3
435 emissions are low, NH_4NO_3 is a much more minor component of aerosols. At present, only a small
436 number of studies have tried to quantify California's total contribution of NO_x and NH_3 derived aerosols
437 to the atmosphere, and no available statewide studies are known to have estimated their net effects on
438 global climate change.

439

440 **5.4.6 Future research needs in California**

441 The recent efforts to quantify the short and long term climate impacts of reactive N at the national and
442 global scales have established sound methodologies for understanding the anthropogenic sources and
443 environmental fate of various forms of reactive N, as well as their relative contribution to climate
444 change (Erismann et al. 2011; Butterbach-Bahl et al. 2011; Pinder et al. 2012a; Pinder et al. 2012b). Across
445 these regional scales, it is provisionally agreed upon by most that the modest cooling effect of reactive N
446 in the near-term is likely to be short-lived as increasing concentrations of N_2O build up in the
447 atmosphere and exacerbate the overall warming trend driven primarily by CO_2 (Figure 5.4.2).

448 While California's contribution to Earth's radiative balance has not been fully assessed in the
449 scientific literature, it is likely that the sources of N, climate forcing processes and overall trends will be
450 similar to those reported in the large-scale regional assessments discussed above. That said, future
451 studies are still needed to confirm whether or not this is true for California in particular. For those

452 interested in pursuing a more comprehensive statewide analysis, the data presented in the preceding
453 mass-balance on key flows of reactive N (e.g., N₂O, NO_x, and NH₃ emissions; N deposition) may serve
454 as a useful starting point for future studies (See Chapter 4; Table 5.4.4). With an eye towards future
455 research, the following studies would be needed to complete a full assessment of California's
456 contribution to climate change through anthropogenic sources of reactive N.

- 457 • Field and modeling studies measuring N₂O emissions from California's diverse annual and
458 perennial cropping systems. These are needed to improve the calibration of soil biogeochemical
459 models and thus reduce the uncertainty of statewide N₂O emissions estimates.
- 460 • Ecological studies quantifying the effects of N deposition on both C sequestration and CH₄
461 emissions in California's natural and agricultural ecosystems.
- 462 • Ecological and atmospheric studies quantifying the effects of tropospheric O₃ on C
463 sequestration by native vegetation and crops in California.
- 464 • Atmospheric studies evaluating the effects of NO_x emitted in California on the formation of O₃,
465 hydroxyl radicals and the decay of CH₄.
- 466 • Atmospheric studies quantifying the radiative effects of aerosols formed from emissions of NO_x
467 and NH₄ in California.

468

469

470

471

472

473

474

475 **References**

- 476 Aber, J.D., McDowell, W., Nadelhoffer, K., Magill, A., Berntson, G., Kamakea, M., McNulty, S.G., Currie,
477 W., Rustad, L., and Fernandez, I. 1998. Nitrogen saturation in northern forest ecosystems.
478 *BioScience* 39: 378–386.
- 479 Akiyama H, Yan XY, & Yagi K (2010) Evaluation of effectiveness of enhanced-efficiency fertilizers as
480 mitigation options for N₂O and NO emissions from agricultural soils: meta-analysis. *Global*
481 *Change Biology* 16(6):1837-1846.
- 482 Anderson, T. L., Charlson R.J., Schwartz S.E., Knutti R., Boucher O., Rodhe H., and Heintzenberg J. 2003.
483 Climate forcing by aerosols—A hazy picture. *Science* 300:1103–1104.
- 484 Arneth, A., Harrison, S. P., Zaehle, S., Tsigaridis, K., Menon, S., Bartlein, P. J., Feichter, J., Korhola, A.,
485 Kulmala, M., O'Donnell, D., Schurgers, G., Sorvari, S., and Vesala, T. 2010. Terrestrial
486 biogeochemical feedbacks in the climate system, *Nature Geoscience* 3:525–532.
- 487 Battye, W., Aneja, V.P., and Roelle, P.A. 2003. Evaluation and improvement of ammonia emission
488 inventories. *Atmospheric Environment* 37:3873–3883.
- 489 Blengini GA, Busto M. 2009. The life cycle of rice: LCA of alternative agri-food chain management
490 systems in Vercelli (Italy). *Journal of Environmental Management* 90: 1512-1522.
- 491 Bouwman, A.F., Boumans, L.J.M. and Batjes, N.H. 2002a. Emissions of N₂O and NO from fertilised fields:
492 Summary of available measurement data. *Global Biogeochemical Cycles* 16(4), art. no. 1058.
- 493 Bouwman, A.F., Boumans, L.J.M. and Batjes, N.H. (2002b). Modeling global annual N₂O and NO
494 emissions from fertilised fields. *Global Biogeochemical Cycles* 16(4), art. no. 1080.

- 495 Burger, M., Jackson, L.E., Lundquist, E.J., Louie, D.T., Miller, R.L., Rolston, D.E., and Scow, K.M. 2005.
496 Microbial responses and nitrous oxide emissions during wetting and drying of organically and
497 conventionally managed soil under tomatoes. *Biology and Fertility of Soils* 42:109-118.
- 498 Butterbach-Bahl, K., Nemitz, E., and Zaehle, S. 2011. The European nitrogen assessment. Cambridge
499 University Press, Cambridge.
- 500 CARB (California Air Resources Board) 2009. California's 1990-2004 Greenhouse Gas Emissions Inventory
501 and 1990 Emissions Level: Technical Support Document. California Environmental Protection
502 Agency, Air Resources Board, Sacramento, California.
- 503 CARB (California Air Resources Board), 2010. California greenhouse gas inventory for 2000-2008.
504 Sacramento, CA: California Environmental Protection Agency, Air Resources Board.
- 505 Carlsson-Kanyama, A. 1998. Climate change and dietary choices - how can emissions of greenhouse
506 gases from food consumption be reduced? *Food Policy* 23(3/4): 277-293.
- 507 CEC (California Energy Commission) 2006. Inventory of California greenhouse gas emissions and sinks:
508 1990 to 2004. CEC-600-2006- 013-SF. PIER Energy-Related Environmental Research Program.
509 Sacramento, California.
- 510 Compton, J. E., Harrison J.A., Dennis R.L., Greaver T.L., Hill B.H., Jordan S.J., Walker J., and Campbell H.V.
511 2011. Ecosystem services altered by human changes in nitrogen cycle: A new perspective for US
512 decision making. *Ecology Letters* 14:804-815.
- 513 Crutzen, P.J., Mosier, A. R., Smith, K. A., and Winiwarter, W. 2008. N₂O release from agro-biofuel
514 production negates global warming reduction by replacing fossil fuels. *Atmospheric Chemistry
515 and Physics* 8:385-389.
- 516 Davidson, E.A. 2009. The contribution of manure and fertilizer nitrogen to atmospheric nitrous oxide
517 since 1860. *Nature Geoscience* 2:659-662.

- 518 De Gryze, S.D., et al., 2009. Modeling shows that alternative soil management can decrease
519 greenhouse gases. *California Agriculture* 63(2):84–90.
- 520 De Gryze, S.D., et al., 2010. Simulating greenhouse gas budgets of four California cropping systems
521 under conventional and alternative management. *Ecological Applications*, 20, 1805–1819.
- 522 EEA (European Environment Agency) 2010. Snapshot of Global Greenhouse Gas Emissions. Copenhagen,
523 Denmark. pp.16.
- 524 Erisman, J.W., Galloway, J., Seitzinger S., Bleeker, A., and Butterbach-Bahl, K. 2011. Reactive nitrogen in
525 the environment and its effect on climate change. *Current Opinion in Environmental*
526 *Sustainability* 3:281–290.
- 527 Felzer, B.S.F., Kicklighter, D.W., Melillo, J.M., Wang, C., Zhuang, Q., and Prinn, R. G. 2004. Ozone effects
528 on net primary production and carbon sequestration in the conterminous United States using a
529 biogeochemistry model. *Tellus* 56B, 230–248.
- 530 Felzer, B.S., Reilly, J.M., Melillo, J., Kicklighter ,D.W., Sarofim M.C., Wang C., Prinn R.G., and Zhuang Q.
531 2005. Future effects of ozone on carbon sequestration and climate change policy using a
532 biogeochemistry model. *Climatic Change* 73:345–373.
- 533 Fenn, M.E., Poth, M.A. and Johnson, D.W. 1996. Evidence for nitrogen saturation in the San Bernardino
534 Mountains in Southern California. *Forest Ecology and Management* 82:211–230.
- 535 Fenn, M.E., Poth, M.A., Aber, J.D., Baron, J.S., Bormann, B.T., Johnson, D.W., Lemly, A.D., McNulty, S.G.,
536 Ryan, D.F. and Stottlemeyer, R. 1998. Nitrogen excess in North American ecosystems:
537 Predisposing factors, ecosystems responses, and management strategies. *Ecological*
538 *Applications* 8:706–733.

- 539 Fenn, M.E., Baron, J.S., Allen, E.B., Rueth, H.M., Nydick, K.R., Geiser, L., Bowman, W.D., Sickman, J.O.,
540 Meixner, R T., Johnson, D.W., and Neitlich, P. 2003. Ecological Effects of Nitrogen Deposition in
541 the Western United States. *BioScience* 53(4):404-420.
- 542 Forster, P. et al. 2007. The physical science basis. Contribution of working group I to the fourth
543 assessment report of the intergovernmental panel on climate change: changes in atmospheric
544 constituents and in radiative forcing. In: *Climate Change 2007* (ed. Solomon, S. et al.). Cambridge
545 University Press, Cambridge, UK, New York, NY, pp. 129–234.
- 546 Grantz, D.A. and Shrestha, A. 2006. Tropospheric ozone and interspecific competition between yellow
547 nutsedge and Pima cotton. *Crop Sci.* 46:1879–1889.
- 548 Haden, V.R., Dempsey, M., Wheeler, S., Salas, W., Jackson, L.E. 2012. Use of local greenhouse gas
549 inventories to prioritize opportunities for climate action planning and voluntary mitigation by
550 agricultural stakeholders in California. *Journal Environmental Planning and Management* In
551 press. DOI:10.1080/09640568.2012.689616.
- 552 Holmes C. D., M.J. Prather, O.A. Søvde and G. Myhre 2013. Future methane, hydroxyl, and their
553 uncertainties: key climate and emission parameters for future predictions. *Atmospheric
554 Chemistry and Physics*, 13, 285–302
- 555 Horwath, W., Burger, M. 2012. Assessment of Baseline Nitrous Oxide Emissions in California Cropping
556 Systems. Contract No. 08-324, California Air Resources Board, Sacramento, CA.
- 557 IPCC (Intergovernmental Panel on Climate Change) 2001 *Climate change 2001: the scientific basis*.
558 Intergovernmental Panel on Climate Change. Cambridge, UK: Cambridge University Press.
- 559 IPCC (Intergovernmental Panel on Climate Change) 2006. 2006 IPCC Guidelines for National Greenhouse
560 Gas Inventories, Prepared by the National Greenhouse Gas Inventories Program, Eggleston H.S.,
561 Buendia L., Miwa K., Ngara T. and Tanabe K. (eds). Published: IGES, Japan.

- 562 IPCC (Intergovernmental Panel on Climate Change) 2007. Climate Change 2007: Synthesis Report.
563 Contribution of Working Groups I, II and III to the Fourth Assessment. Bernstein, L., Bosch, P.
564 Canziani, O., Chen, Z., Christ, R., Davidson, O., Hare, W., Huq, S., Karoly, D., Kattsov, V.,
565 Kundzewicz, Z.W., Liu, J., Lohmann, U., Manning, M., Matsuno, T., Menne, B., Metz, B., Mirza,
566 M., Nicholls, N., Nurse, L., Pachauri, R., Palutikof, J., Parrry, M., Qin, D., Ravindranath, N.H.,
567 Reisinger, A., Ren, J., Riahi, K., Rosenzweig, C., Rusticucci, M., Schneider, S., Sokona, Y., Solomon,
568 S., Stott, P., Stouffer, R., Sugiyama, T., Swart, R.J., Tirpak, D., Vogel, C., Yohe, G., Published:
569 Geneva, Switzerland. pp. 73.
- 570 Janssens, I.A., Dieleman, W., Luysaert, S., Subke, J.A., Reichstein, M., Ceulemans, R., Ciais, P., Dolman,
571 A.J., Grace, J., Matteucci, G., Papale, D., Piao, S.L., Schulze, E.D., Tang, J., and Law, B.E. 2010.
572 Reduction of forest soil respiration in response to nitrogen deposition. *Nature Geoscience*
573 3(5):315–322.
- 574 Kanter D., Mauzerall D.L., Ravishankara A.R., Daniel J.S., Portmann R.W., Gabriel P.M., Moomaw W.R., &
575 Galloway J.N. (2013) "A post-Kyoto partner: Considering the stratospheric ozone regime as a
576 tool to manage nitrous oxide", *Proceedings of the National Academy of Sciences*, 110(12):4451-
577 4457
- 578 Knorr, M., Frey, S.D., and Curtis, P.S. 2005. Nitrogen additions and litter decomposition: a meta-analysis.
579 *Ecology* 86(12):3252–3257.
- 580 Kongshaug, G. 1998. Energy Consumption and Greenhouse Gas Emissions in Fertilizer Production. IFA
581 Technical Conference, Marrakech, Morocco, 28 September-1 October, 1998, 18pp.
- 582 Ladha, J.K., Reddy, C.K., Padre, A.T., and van Kessel, C. 2011. Role of Nitrogen Fertilization in Sustaining
583 Organic Matter in Cultivated Soils. *Journal of Environmental Quality* 40:1756–1766.

- 584 Lillywhite R, Chandler D, Wyn G, Lewis K, Firth C, Schmutz U, Halpin D. 2007. Environmental Footprint
585 and Sustainability of Horticulture (including Potatoes) - A Comparison with other Agricultural
586 Sectors. Report to the Department of Environment, Food, and Rural Affairs. Warwick, UK:
587 University of Warwick.
- 588 Linqvist, B., van Groenigen, K.J., Adviento-Borbe, M.A., Pittelkow, C., and van Kessel, C. 2012. An
589 agronomic assessment of greenhouse gas emissions from major cereal crops. *Global Change*
590 *Biology* 18:194-209.
- 591 Liu, L.L., and Greaver, T.L. 2009. A review of nitrogen enrichment effects on three biogenic GHGs: the
592 CO₂ sink may be largely offset by stimulated N₂O and CH₄ emission. *Ecology Letters*
593 12(10):1103–1117.
- 594 Matson, P., Lohse, K.A., and Hall, S.J., 2002. The Globalization of Nitrogen Deposition: Consequences for
595 Terrestrial Ecosystems. *AMBIO: A Journal of the Human Environment* 31(2):113-119.
- 596 Natural Resources Canada (NRCAN). 2007. Canadian Ammonia Producers: Benchmarking Energy
597 Efficiency and Carbon Dioxide Emissions. Canadian Industry Program for Energy Efficiency,
598 Natural Resources Canada. [http://oee.nrcan.gc.ca/industrial/technical-](http://oee.nrcan.gc.ca/industrial/technical-info/benchmarking/ammonia/index.cfm?attr=24)
599 [info/benchmarking/ammonia/index.cfm?attr=24](http://oee.nrcan.gc.ca/industrial/technical-info/benchmarking/ammonia/index.cfm?attr=24)
- 600 Ollinger, S., Aber, J., and Reich, P. 1997. Simulating ozone effects on forest productivity: Interactions
601 among leaf-, canopy-, and stand-level processes. *Ecological Applications* 7:1237–1251.
- 602 Pan, Y., Birdsey, R., Hom, J., and McCullough, K. 2009. Separating effects of changes in atmospheric
603 composition, climate and land-use on carbon sequestration of U.S. mid-Atlantic temperate forests.
604 *Forest Ecology and Management* 259(2):151–164.
- 605 Park S., Croteau P., Boering K. A., Etheridge D. M, Ferretti D., Fraser P. J., Kim K.R., Krummel P. B.,
606 Langenfelds R. L., van Ommen T. D., Steele L. P., Trudinger C. M. 2012. Trends and seasonal

607 cycles in the isotopic composition of nitrous oxide since 1940. *Nature Geoscience*, 5 (4): 261-
608 265.

609 Parry, M.L., Canziani, O.F., Palutikof, J.P., van der Linden, P.J., and Hanson, C.E. (Eds): IPCC: Climate
610 Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the
611 Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Published:
612 Cambridge University Press, Cambridge, UK.

613 PE International. 2009. GaBi 4 Professional. (Life cycle inventory database). www.gabi-software.com

614 Pinder, R., Davidson, E., Goodale, C., Greaver, T., Herrick, J., and Liu, L. 2012a. Climate change impacts of
615 US reactive nitrogen. *Proceedings of the National Academy of Sciences* 109(20):7671–7675.

616 Pinder, R.W., Bettez, N.D., Bonan, G.B., Greaver, T.L., Wieder, W.R., Schlesinger, W.H., and Davidson,
617 E.A. 2012b. Impacts of human alteration of the nitrogen cycle in the US on radiative forcing,
618 *Biogeochemistry*, In press. DOI 10.1007/s10533-012-9787-z.

619 Powers, R.F., and Reynolds, P.E. 1999. Ten-year responses of ponderosa pine plantations to repeated
620 vegetation and nutrient control along an environmental gradient. *Canadian Journal of Forest*
621 *Research* 29:1027–1038.

622 Ravishankara A.R., Daniel J.S., & Portmann R.W. (2009) Nitrous Oxide (N₂O): The Dominant Ozone-
623 Depleting Substance Emitted in the 21st Century. *Science* 326(5949):123-125.

624 Robertson G.P. & Vitousek P.M. (2009) Nitrogen in Agriculture: Balancing the Cost of an Essential
625 Resource. *Annual Review of Environment and Resources*, Annual Review of Environment and
626 Resources), Vol 34, pp 97-125.

627 Shine, K. P., Fuglestedt, J. S., Hailemariam, K. and Stuber, N. 2005. Alternatives to the global warming
628 potential for comparing climate impacts of emissions of greenhouse gases. *Climatic Change*
629 68:281–302.

- 630 Shine, K.P., Berntsen, T.K., Fuglestvedt, J.S., Skeie, R.B., and Stuber, N. 2007. Comparing the climate
631 effect of emissions of short and long lived climate agents. *Philosophical Transactions of the*
632 *Royal Society A* 365:1903–1914.
- 633 Shindell, D.T., Faluvegi, G., Koch, D.M., Schmidt, G.A., Unger, N., and Bauer S.E. 2009. Improved
634 attribution of climate forcing to emissions. *Science* 326:716-718.
- 635 Shrestha, A., and D.A. Grantz. 2005. Ozone impacts on competition between tomato and yellow
636 nutsedge: Above- and below-ground. *Crop Science* 45:1587–1595.
- 637 Sitch, S., Cox, P.M., Collins, W.J., Huntingford, C. 2007. Indirect radiative forcing of climate change
638 through ozone effects on the land-carbon sink. *Nature* 448(7155): 791–794.
- 639 Smart, D.R., Alsina, M.M., Wolff, M.W., Matiasek, M.G., Schellenberg D.L., Edstrom J.P., Brown P.H., and
640 Scow, K.M. Chapter 12: N₂O Emissions and Water Management in California Perennial Crops, In:
641 Understanding Greenhouse Gas Emissions from Agricultural Management; Guo, L., et al.; ACS
642 Symposium Series; American Chemical Society, Published: Washington, DC, 2011.
- 643 United States Department of Agriculture Economic Research Service (2012) ARMS Farm Financial and
644 Crop Production Practices: Tailored Reports. (Washington, DC)
- 645 Smith, P.D., Martino, Z., Cai, D., Janzen, H., Kumar, P, McCarl, B., Ogle, S., O'Mara, F., Rice, C., Scholes,
646 B., and Sirotenko, O. 2007. Agriculture: In Climate Change 2007: Mitigation. Contribution of
647 Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate
648 Change [Metz B, Davidson OR, Bosch PR, Dave R, Meyer LA (eds)], Published: Cambridge
649 University Press, Cambridge, United Kingdom and New York, NY, USA.
- 650 Smith, W.N., et al., 2010. A tool to link agricultural activity data with the DNDC model to estimate GHG
651 emission factors in Canada. *Agriculture, Ecosystems and Environment*, 136, 301–309.

- 652 Snyder CS, Bruulsema TW, Jensen TL, Fixen PE. 2009. Review of greenhouse gas emissions from crop
653 production systems and fertilizer management effects. *Agriculture, Ecosystems, and*
654 *Environment* 133: 247-266.
- 655 Steenwerth, K.L.,and Belina, K.M. 2010. Vineyard weed management practices influence nitrate
656 leaching and nitrous oxide emissions *Agriculture, Ecosystems and Environment* 138:127–131.
- 657 Stehfest, E., and Bouwman, L., 2006. N₂O and NO emission from agricultural fields and soils under
658 natural vegetation: summarizing available measurement data and modeling of global annual
659 emissions. *Nutrient Cycling in Agroecosystems* 74:207-228.
- 660 Suddick, E.C., Steenwerth, K., Garland, G.M., Smart, D.R., and Six, J. 2011. Discerning agricultural
661 management effects on nitrous oxide emissions from conventional and alternative cropping
662 systems: A California case study. In: *Understanding Greenhouse Gas Emissions from Agricultural*
663 *Management*; Guo, L., A.S. Gunasekara, and L.L. McConnel; ACS Symposium Series Vol. 1072;
664 American Chemical Society, Published: Washington, DC, 2011. pp. 203-226.
- 665 Sutton, M.A., Simpson, D., Levy, P.E., Smith, R.I., Reis, S., van Oijen, M., de Vries, W. 2008. Uncertainties
666 in the relationship between atmospheric nitrogen deposition and forest carbon sequestration,
667 *Global Change Biology* 14(9):2057–2063.
- 668 Syakila, A., C. Kroeze. 2011. The Global Nitrous Oxide Budget Revisited. *Greenhouse Gas Measurement*
669 *and Management* 1 (1): 17–26.
- 670 Thomas RQ, Canham CD, Weathers KC, Goodale CL (2010) Increased tree carbon storage in response to
671 nitrogen deposition in the US, *Nature Geoscience* 3(1):13–17.
- 672 Velders G.J.M., Andersen S.O., Daniel J.S., Fahey D.W., & McFarland M. (2007) The importance of the
673 Montreal Protocol in protecting climate. *Proceedings of the National Academy of Sciences*
674 104(12):4814-4819.

675 Wiesen P. (2010) Abiotic Nitrous Oxide Sources: Chemical Industry and Mobile and Stationary
676 Combustion Systems. *Nitrous Oxide and Climate Change*, ed Smith K (Earthscan, London, UK)
677 White, A., Cannell, M. G. R., and Friend, A.D. 1999. 'Climate Change Impacts on Ecosystems and the
678 Terrestrial Carbon Sink: A New Assessment', *Global Environmental Change* 9:S21–S30.
679 Wood S, Cowie A. 2004. A review of greenhouse gas emissions factors for fertilizer production.
680 Cooperative Research Centre for Greenhouse Accounting, Research and Development Division,
681 State Forests of New South Wales. Accessed at [http://www.ieabioenergy-](http://www.ieabioenergy-task38.org/publications/GHG_Emission_Fertilizer%20Production_July2004.pdf)
682 [task38.org/publications/GHG_Emission_Fertilizer%20Production_July2004.pdf](http://www.ieabioenergy-task38.org/publications/GHG_Emission_Fertilizer%20Production_July2004.pdf) on June 7, 2011.
683
684
685
686
687
688
689
690
691
692
693
694
695
696
697

698

699 Box 5.4.1 Nitrous oxide: a greenhouse gas and an ozone depleting substance [\[Return to text\]](#)

700 Nitrous oxide (N₂O) contributes to two distinct global environmental issues: climate change and
701 stratospheric ozone depletion. As a greenhouse gas, N₂O is 298 times more potent than carbon dioxide
702 and is the third most abundantly emitted greenhouse gas (after carbon dioxide and methane) (Forster
703 et al. 2007). Overall, N₂O is responsible for approximately 8% of the global anthropogenic greenhouse
704 gas emissions that contribute to climate change (Forster et al. 2007). While N₂O is a relatively long-lived
705 greenhouse gas, in the stratosphere solar radiation eventually degrades the molecule to form the free
706 radical nitric oxide (NO) which has additional implications for the separate issue of ozone depletion. Free
707 radicals such as NO catalyze secondary reactions that convert ozone (O₃) and a single oxygen atom (O)
708 into two molecules of oxygen gas (O₂) (e.g., $O + O_3 \rightarrow 2 O_2$). Consequently, increased N₂O emissions
709 also ultimately lead to a buildup of NO in the stratosphere, the depletion of the Earth's ozone layer and
710 the subsequent loss of protection from the sun's ultraviolet light. At present, N₂O is the most
711 abundantly emitted ozone depleting substance, and will be for the remainder of the 21st century if
712 emissions continue at their current pace (Ravishankara et al. 2009).

713 N₂O is not the only substance to have these dual properties. Many ozone depleting substances,
714 including chlorofluorocarbons (CFCs), methyl bromide and several other gas species are also highly
715 potent greenhouse gases. And yet N₂O and CFCs are controlled under two different treaties: CFCs under
716 the 1987 Montreal Protocol and N₂O under the 1997 Kyoto Protocol. The Montreal Protocol is
717 considered a model of global environmental cooperation. Under the Montreal framework, the
718 production and commercial use of ozone depleting substances (with the notable exception of N₂O) have
719 been reduced by approximately 97% globally (Velders et al. 2007). This success in reducing the emissions

720 of other ozone depleting substances is the main reason that N₂O is now the dominant remaining ozone
721 depleting substance. In contrast, the Kyoto Protocol significantly undershot its first phase targets and
722 the parameters of its second commitment period (with a diminished membership) remain unclear.
723 Kyoto's uneven track record has motivated some to explore how the Montreal Protocol might be
724 expanded to include N₂O and thus maximize the dual ozone and climate benefits of the existing policy
725 framework (Kanter et al. 2013).

726 In California, the use of N fertilizers and livestock manure in agriculture are the largest sources
727 of anthropogenic N₂O emissions. Other sources of N₂O include fossil fuel combustion, nitric and adipic
728 acid production, biomass burning and wastewater. Chapters 7 and 8 of this assessment evaluate a range
729 of technical and policy strategies for mitigating N₂O emissions from these economic sectors. Practices to
730 improve fertilizer use efficiency by optimizing N rates, split applications, controlled release fertilizers,
731 nitrification inhibitors, fertigation technologies and other types of precision agriculture have the
732 potential to reduce N₂O emissions without adverse effects on crop yields (Robertson and Vitousek
733 2009). In particular, a recent review of 35 studies found that nitrification inhibitors and controlled
734 release fertilizers on average can reduce N₂O emissions by approximately 38% and 35% respectively
735 (Akiyama et al. 2009) and are steadily increasing their market share (USDA ERS 2012). Considerable
736 progress has also been made with the adoption of catalytic conversion for both stationary and mobile
737 combustion sources and in the processes used for nitric acid production, with the added benefit of also
738 often reducing NO_x emissions (Wiesen 2010). Likewise, any of the agricultural strategies for reducing
739 N₂O are also likely to have positive environmental co-benefits by reducing other forms of nitrogen
740 pollution that diminish California's water and air quality.

741

742

743 **Box 5.4.2 Climate impacts of fertilizer manufacture** [\[Return to text\]](#)

744 Use of synthetic nitrogen fertilizer typically accounts for a high percentage of greenhouse gas (GHG)
745 emissions in conventional crop production. In addition to soil emissions resulting from the application
746 of fertilizers on crop fields, the production of the fertilizer itself accounts for a large portion of total
747 emissions. According to a selection of food life cycle assessment studies (Carlsson-Kanyama 1998;
748 Blengini and Busto 2009), the proportion of total GHG emissions attributable to fertilizer production can
749 range from less than 5% to 18%, depending on the type of food product being analyzed and the system
750 boundaries of the study. For some horticultural crops, it can account for up to 70% of CO₂ emissions
751 (not counting other GHGs) up to farmgate (Lillywhite et al. 2007). Moreover, fertilizer production has
752 been estimated to account for 1.2% of the world's total energy use and 1.2% of the total GHG emissions
753 (Kongshaug 1998).

754 Nitrogenous fertilizer production relies on the Haber-Bosch process, an industrial process that
755 synthesizes ammonia (NH₃) by mixing nitrogen from the air with hydrogen under high temperature and
756 pressure conditions, requiring a large amount of energy - approximately 25-35 GJ/tonne NH₃ (DOE
757 2000). Approximately 80% of the world's NH₃ production uses natural gas as both the hydrocarbon
758 feedstock (as the source of hydrogen) and as the energy source, resulting in CO₂ emissions as the
759 dominant component of GHG emissions (Wood and Cowie 2004). Various studies have estimated
760 emissions in NH₃ production to range from 1150 to 2800 g CO₂-equivalent (CO₂-e) per kg NH₃, or 1402
761 to 3415 g CO₂-e per kg N content (Wood and Cowie 2004, PE International 2009). Wood and Cowie
762 (2004) report that the transparency of reviewed reports was inadequate to explain these large
763 differences between estimates, but that a large portion of the variation is likely due to variation in plant
764 efficiencies, the use of alternative fossil fuels, and differences in methods for accounting for the steam

765 exports that result from the process (which can be used for electricity generation and therefore can be
766 counted as a credit toward the fertilizer emissions, due to offsetting of other electricity generation). A
767 study commissioned by Natural Resources Canada (2007) confirms that measures taken by Canadian
768 urea production plants to improve overall energy efficiency and re-use CO₂ (see below) result in
769 substantially lower emissions relative to facilities in other parts of the world.

770 Manufacture of ammonium nitrate, a fertilizer used commonly in California and around the
771 world, results in even higher GHG emissions because, after the initial synthesis of NH₃, it must be
772 oxidized at high temperature and pressure to create nitric acid, a process that, while being exothermic
773 (heat-releasing, and thus a net energy generator), also results in N₂O as a by-product. NH₃ is then
774 neutralized with aqueous nitric acid (HNO₃) to produce ammonium nitrate (NH₄NO₃). The total CO₂-e
775 emissions, therefore, essentially consist of both the CO₂ emissions from the initial NH₃ production and
776 the N₂O emissions from the subsequent nitric acid production. Different studies have calculated
777 emissions ranging from 1000 to 2381 g CO₂-e per kg NH₄NO₃, or 2985 to 7109 g CO₂-e per kg N (Wood
778 and Cowie 2004, PE International 2009).

779 Urea is synthesized by combining NH₃ and CO₂ under high pressure to form ammonium
780 carbonate, which is then dehydrated under heat to form urea and water. Emissions calculations vary
781 depending on whether CO₂ use in the production process is subtracted from the CO₂ emissions from
782 NH₃ production, and are reported as 420 to 1849 g CO₂-e per kg product, or 913 to 4018 g CO₂-e per kg
783 N (Wood and Cowie 2004, PE International 2009). However, while urea may have a lower footprint in its
784 production phase, due to the capture and re-use of CO₂ Snyder et al. (2009) point out that some or all of
785 this CO₂ may be emitted again from the soil after application.

786 For perspective, we can calculate rough estimates for CO₂-equivalent soil emissions resulting
787 from application of these fertilizer products to agricultural fields. The IPCC default emissions factor for

788 direct N₂O emissions (the emissions resulting from direct nitrification and denitrification pathways for
789 fertilizer N) is 1% of applied N (IPCC 2006, p 11.11). In the case of NH₃, which is 82% N by mass, the
790 emissions would thus be estimated as 8.2 g N₂O-N per kg ammonia (calculated as 1% of 820 g NH₃-N).
791 This figure translates to 12.89 g N₂O, and 3816 g CO₂-e per kg product, or 4654 g CO₂-e per kg N applied
792 (using the 100-yr global warming potential of 296 for N₂O). One should note that these calculations do
793 not include indirect emissions - those arising from volatilization, leaching, and runoff of fertilizer N,
794 some of which later becomes N₂O in off-site locations. As with direct emissions, these processes can
795 vary tremendously according to soil type, climate, and management practices, but the default factors
796 suggested by IPCC (2006) for use when these specific variables are unknown, would raise the total
797 emissions estimates by an additional 33%. At any rate, the GHG emissions produced in manufacture of
798 the fertilizer range from 20 to 150% of emissions produced after field application, or 23 to 60% of total
799 emissions attributable to N fertilizer use, depending on fertilizer product, manufacturing efficiency, and
800 additional variables. Given that many field studies have found that field emissions in specific locations
801 and conditions may in fact be much lower than the IPCC default factors (Snyder et al. 2009), the
802 proportion of life cycle GHG emissions attributable to fertilizer production may be correspondingly
803 higher. Nitrogenous fertilizer production, therefore, contributes substantially to total climate change
804 impacts of synthetic fertilizer use.

805

806

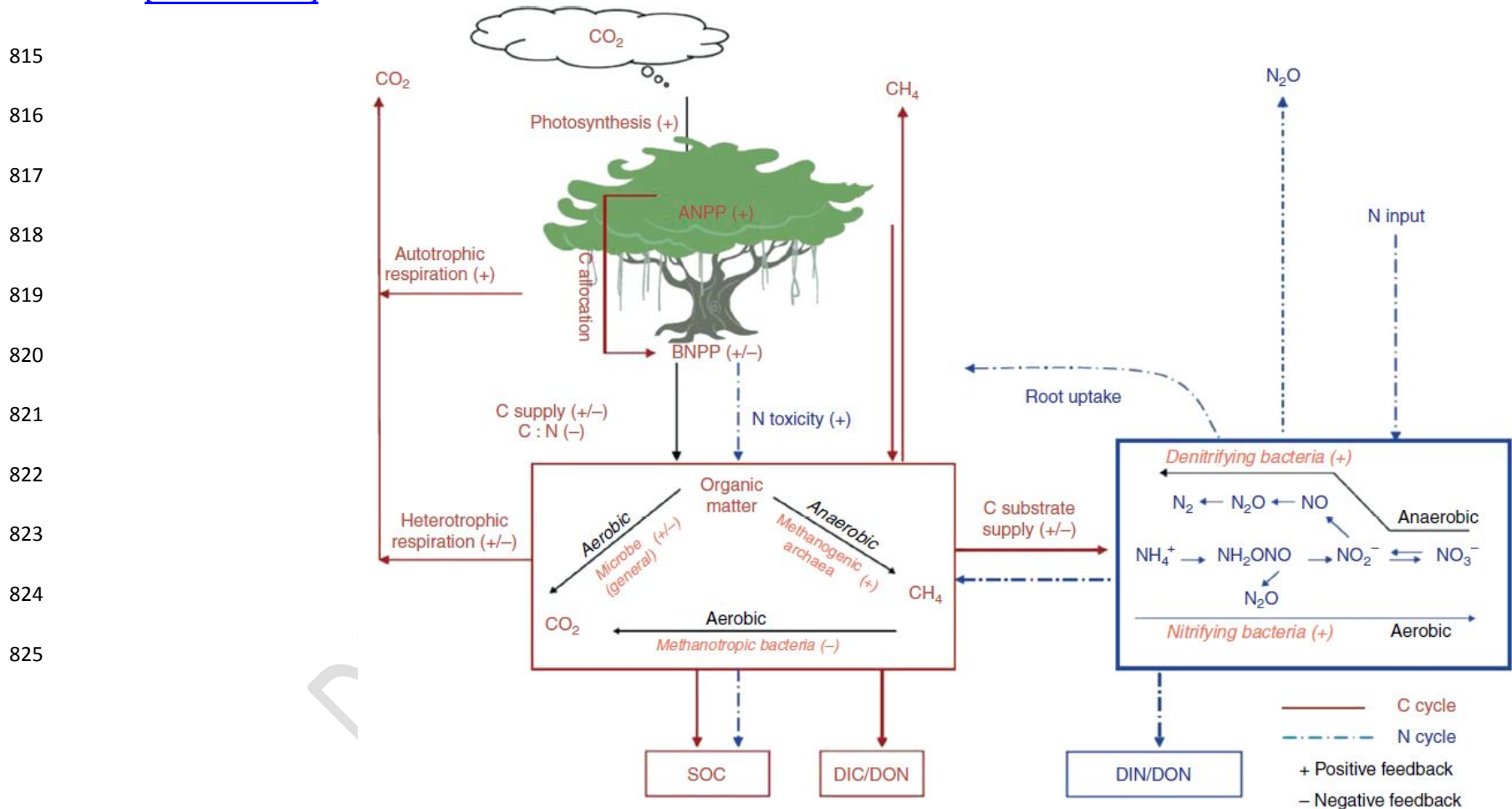
807

808

809

DRAFT: Stakeholder Review

811 **Figure 5.4.1 Potential mechanisms regulating the terrestrial ecosystem responses of CO₂, CH₄ and N₂O production and consumption to**
 812 **increased availability of reactive N.** ANPP = aboveground net primary productivity; BNPP = belowground net primary productivity; SOC = soil
 813 organic carbon; DOC = dissolved organic carbon; DIN = dissolved inorganic nitrogen; DON = dissolved organic nitrogen. Source: Liu and Greaver
 814 2009. [Return to text](#)

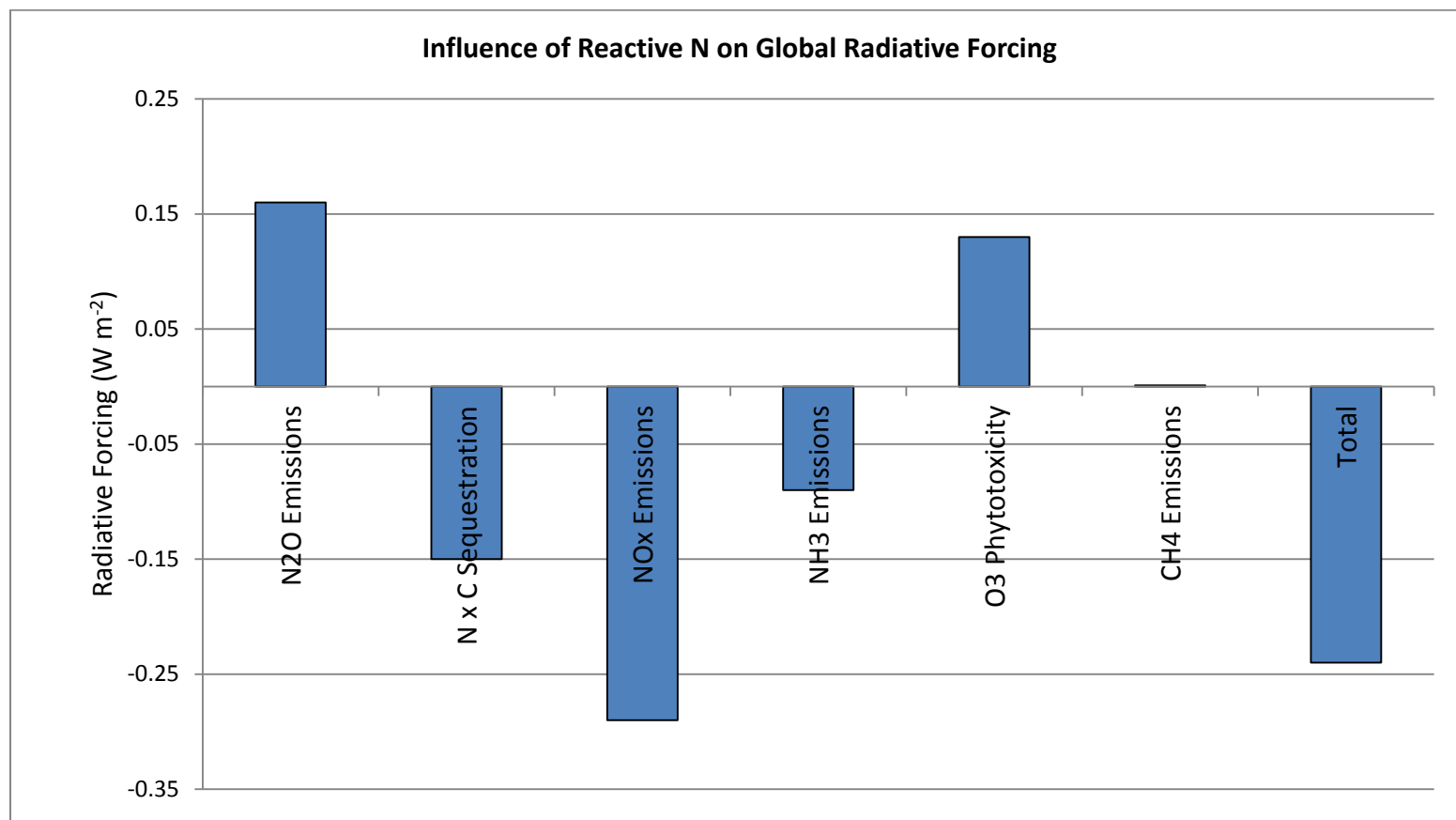


826 **Figure 5.4.2 Types of uncertainty in nitrogen’s impact on global climate regulation.** This figure reflects the amount of evidence and level of
 827 agreement for the various nitrogen-related biogeochemical processes that influence climate regulation over time. [\[Return to text\]](#)

	Low agreement	Medium agreement	High agreement
Low evidence		<p>Aerosols formed from nitrogen oxides and ammonia reflect solar radiation leading to short term cooling effects</p>	
Medium evidence		<p>Anthropogenic nitrogen has a cooling effect on climate in the near-term (20yr), but a net warming effect in the long-term</p> <p>Nitrous oxide emissions, mostly from agriculture, accounts for about 3% of CA’s total GHG emissions</p>	<p>Nitrogen deposition increases the flux of methane from anaerobic soils leading to a net warming effect on climate</p> <p>Terrestrial carbon sequestration stimulated by N deposition has a net cooling effect on climate</p> <p>Ground-level ozone has adverse effects on plant carbon sequestration which lead to a net warming effect on climate</p> <p>Stratospheric ozone increases the hydroxyl radicals and reduces the atmospheric lifetime methane, which have a cooling effect on climate</p>
High evidence			<p>Nitrous oxide emissions have a long-term net warming effect on the climate</p> <p>Human activities that increase reactive nitrogen in the environment have a mix of competing warming and cooling effects on climate</p>

828

829 **Figure 5.4.3 Influence of anthropogenic reactive N on global radiative forcing on the present climate.** Radiative forcing values above zero imply
830 a warming effect on the present global climate, while negative values indicate a cooling effect. “N x C Sequestration” includes effects of N
831 deposition on C sequestration and CO₂ efflux in terrestrial and aquatic systems and mineralization in soil. “NO_x emissions” contains effects of O₃
832 and other aerosols formed from reactions with NO_x. “NH₃ emissions” are particulates and other aerosols formed from NH₃ in the atmosphere.
833 “CH₄ emissions” contains only the effects of N on CH₄ from soils, while the effects of N on the atmospheric lifetime of CH₄ are included in NO_x
834 emissions. Uncertainty for total global radiative forcing ranged from -0.5 to +0.2 to W m⁻². Sources: Adapted from Erisman et al. 2011; Shindell
835 et al. 2009 [\[Return to text\]](#)

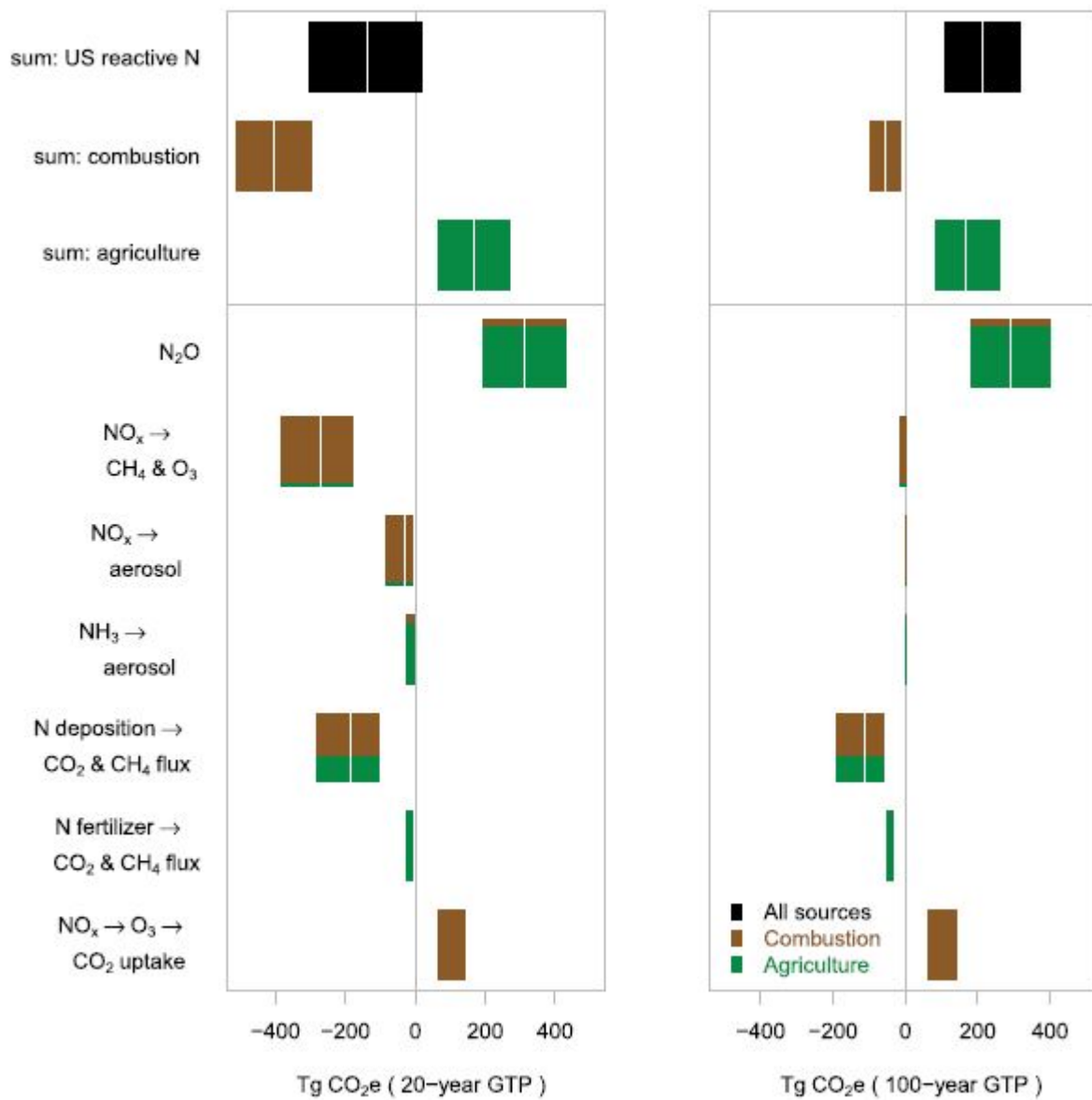


836

837

DRAFT

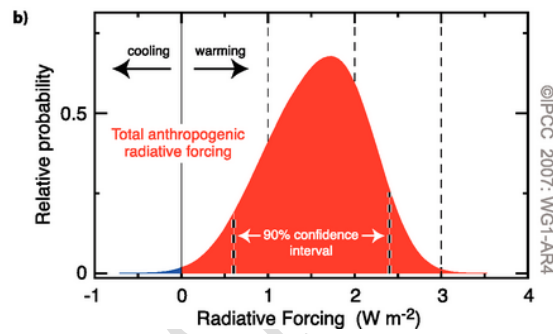
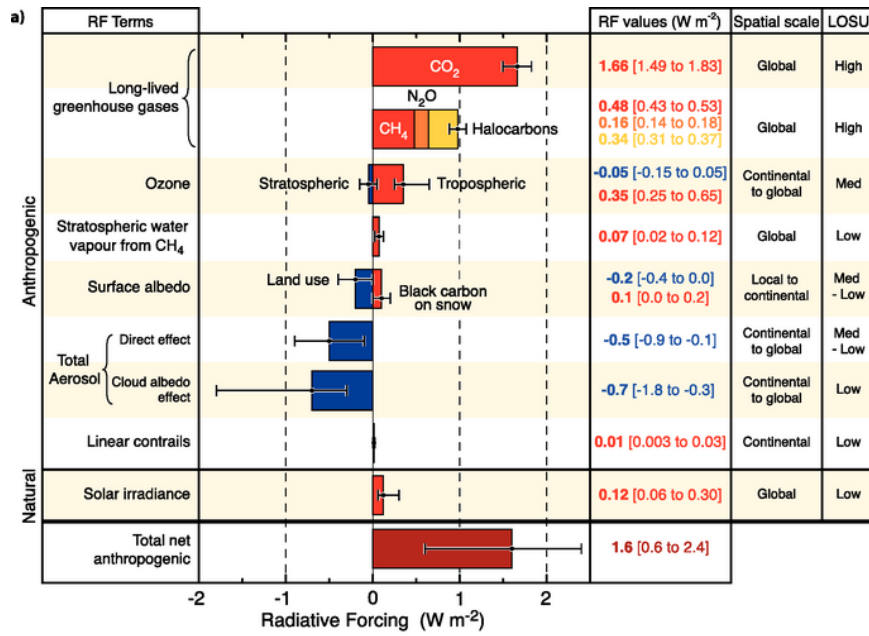
838 **Figure 5.4.4 The climate change impacts of US reactive nitrogen emissions from combustion and**
 839 **agriculture, in common units of equivalent Tg of CO₂ (Tg CO₂e) on a 20-year and 100-year global**
 840 **temperature potential (GTP) basis. The width of the bar denotes the uncertainty range; the white line is**
 841 **the best-estimate; and the color shading shows the relative contribution of combustion and agriculture.**
 842 Source: Pinder et al. 2012a. [\[Return to text\]](#)



843

844 **Figure 5.4.5 Global mean radiative forcings (RF) and their 90% confidence intervals in 2007 for various**
845 **agents and mechanisms (a) and probability distribution of the global mean combined radiative forcing**
846 **from all anthropogenic agents shown in (b).** Columns on the right-hand side indicate best estimates and
847 confidence intervals (RF values); typical geographical extent of the forcing (Spatial scale); and level of
848 scientific understanding (LOSU). Errors for CH₄, N₂O and halocarbons have been combined. The net
849 anthropogenic radiative forcing and its range are also shown. Best estimates and uncertainty ranges can
850 not be obtained by direct addition of individual terms due to the asymmetric uncertainty ranges for
851 some factors; the values given here were obtained from a Monte Carlo technique. Additional forcing
852 factors not included here are considered to have a very low LOSU. Volcanic aerosols contribute an
853 additional form of natural forcing but are not included due to their episodic nature. The range for linear
854 contrails does not include other possible effects of aviation on cloudiness. The distribution is calculated
855 by combining the best estimates and uncertainties of each component. The spread in the distribution is
856 increased significantly by the negative forcing terms, which have larger uncertainties than the positive
857 terms. Source: IPCC 2007. [\[Return to text\]](#)

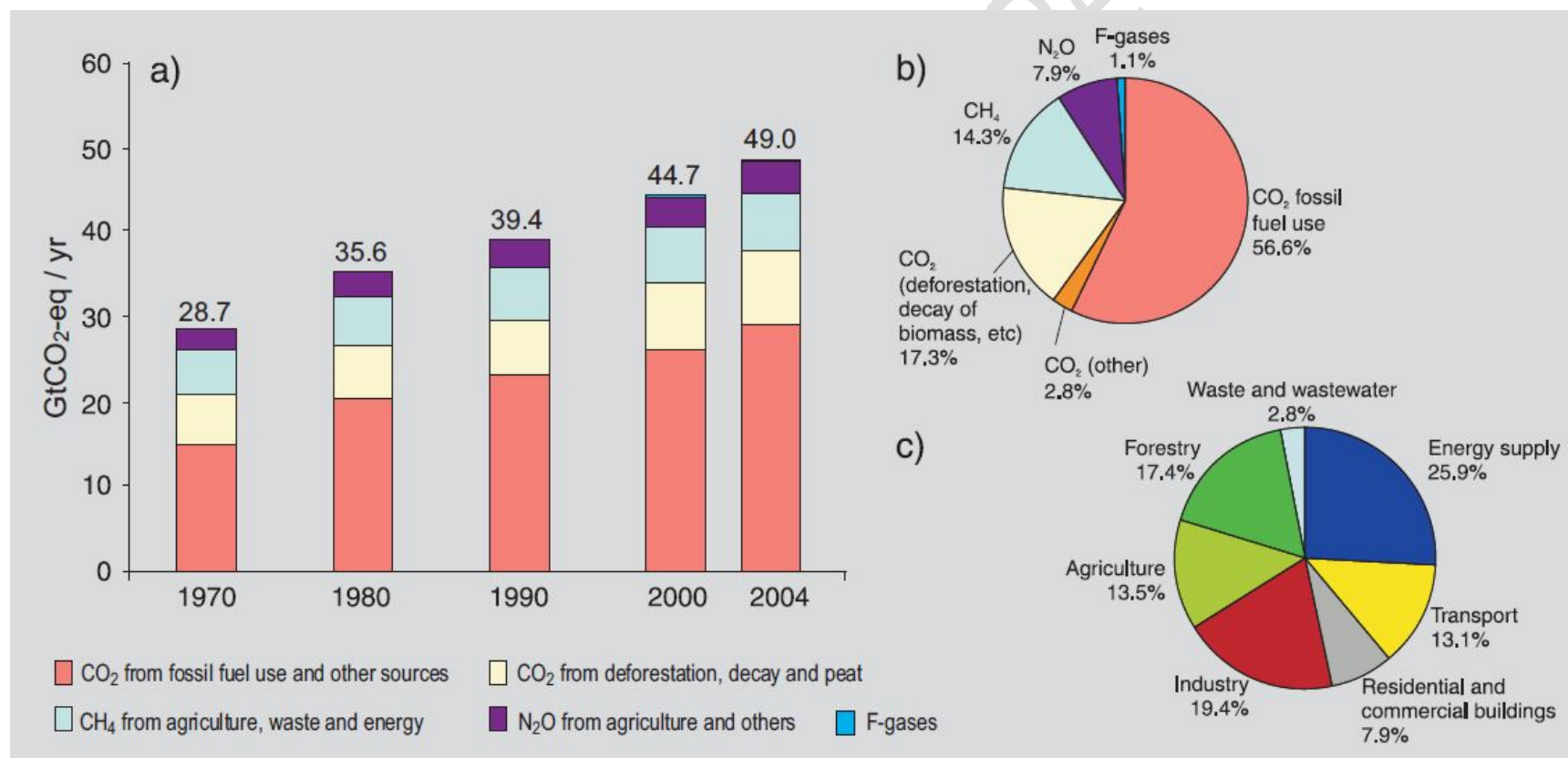
858



859

860 **Figure 5.4.6 Global annual emissions of anthropogenic GHGs from 1970 to 2004 (a). Share of different anthropogenic GHGs in total emissions**
 861 **in 2004 in terms of CO₂e (b). Share of different sectors in total anthropogenic GHG emissions in 2004 in terms of CO₂e (c).** Forestry includes
 862 deforestation. Source: IPCC 2007. [\[Return to text\]](#)

863



864

865

866 **Table 5.4.1 Atmospheric lifetimes and global warming potential (GWP) values for CO₂, CH₄, and N₂O.** Sources: IPCC 2007; IPCC 2001.

867 [\[Return to text\]](#)

Greenhouse Gas	Radiative Efficiency W m ⁻² /ppmv	Atmospheric Lifetime yrs	Global Warming Potential by Integration Time Period (yr)		
			GWP 20 yr	GWP 100 yr	GWP 500 yr
CO ₂	0.01548 ^a	~100 (5-200) ^b	1	1	1
CH ₄	0.00037	12	72	25	7.6
N ₂ O	0.0031	114	289	298	153

868 ^aIPCC 2007 does not give a radiative efficiency for CO₂. IPCC 2001 lists the radiative efficiency of CO₂ as 0.01548 W/m²/ppmv, but emphasizes this figure is to
869 be used only for the computation of global warming potentials.

870 ^bPrecise estimation of the atmospheric lifetime of CO₂ is complicated by the multitude of removal mechanisms involved. Accepted values are around 100
871 years, with a wide error range.

872

873

874

875

876

877 **Table 5.4.2 Processes altered by reactive N that have radiative forcing effects. The size of the short-term (20 yr) and long-term (100 yr) effect**
 878 **is relative to other processes altered by reactive N.** Source: Adapted from Pinder et al. 2012a. [\[Return to text\]](#)
 879

Process altered by		Relative size of effect		Description	References
reactive N	Radiative forcing effect	Short-term	Long-term		
N ₂ O	Warming	Large	Large	Potent & long-lived greenhouse gas from agriculture, fossil fuel combustion, and sewage	Parry et al. 2007; Smith et al. 2007
N deposition/fertilizer → CO ₂ uptake by plants	Cooling	Large	Large	Generally increases C stored in vegetation and soils of natural and agroecosystems	Sutton et al. 2008; Liu and Greaver 2009; Thomas et al. 2010
N deposition/fertilizer → CH ₄ efflux from soil	Warming	Small	Small	Increases CH ₄ emissions and reduces CH ₄ oxidation	Liu and Greaver 2009
NO _x → ground level O ₃ → CO ₂ uptake by plants	Warming	Large	Large	NO _x forms tropospheric O ₃ that damages plant foliage and decreases C storage	Felzer et al. 2004; Sitch et al. 2007; Pan et al. 2009;

					Arneth et al. 2010
NO _x → O ₃ & CH ₄ in atmosphere	Cooling	Large	Small	NO _x effects formation and destruction of O ₃ and CH ₄ in upper atmosphere	Shindell et al. 2009
NO _x → aerosols	Cooling	Medium	Small	Aerosols reflect and scatter solar radiation	Shindell et al. 2009
NH ₃ → aerosols	Cooling	Small	Small	Aerosols reflect and scatter solar radiation	Shindell et al. 2009

880
881
882
883
884
885
886
887
888

DRAFT: Stakeholder Review

889 **Table 5.4.3 California greenhouse gases and percent of annual total emitted in 1990, 2000 and 2009.** Source: CARB 2010.

890 [\[Return to text\]](#)

Greenhouse Gas	1990		2000		2009	
	Emissions	% of Annual	Emissions	% of Annual	Emissions	% of
	MT CO ₂ e	Total	MT CO ₂ e	Total	MT CO ₂ e	Annual Total
CO ₂	390.0	90	408.9	88.1	393.2	86.1
CH ₄	25.1	5.8	28.0	6.0	32.0	7.0
N ₂ O	16.5	3.8	16.0	3.5	15.2	3.3
SF ₆	<1.0	<1.0	1.3	<1.0	1.1	<1.0
Other HFCs*	<1.0	<1.0	10	2.1	15.3	3.3
Total	433.3		463.7		456.8	

891 *Other HFCs includes all other halogenated fluorocarbon gases

892

893

894

895

896 **Table 5.4.4 Estimated emissions of N₂O, NO_x and NH₃ by source and fate in California during 2005.** Percent of each gas emitted by various
 897 sources are also provided. All N₂O emitted was assumed to remain in the atmosphere. NO_x and NH₃, form secondary chemicals, aerosols and
 898 particulates and a certain fraction of the N in these constituents are deposited in California and the remaining are exported beyond state
 899 boundaries. As such, as export to the atmosphere or beyond the state boundary was calculated as the difference between total emissions and
 900 deposition. This table was developed using input and output data from the California N mass-balance developed in Chapter 4 of this report.

901 [\[Return to text\]](#)

Source and Fate of N Emissions	Statewide Emissions					
	N ₂ O		NO _x		NH ₃	
	Gg N yr ⁻¹	%	Gg N yr ⁻¹	%	Gg N yr ⁻¹	%
<i>Source of N Emissions</i>						
Fossil Fuel Combustion	9	23.7	359	88.4	36	13.4
Soil	24	63.2	24	5.9	67	25
Manure	2	5.3	0	0	141	52.6
Upwind sources	0	0	20	4.9	20	7.5
Wastewater	2	5.3	0	0	0	0
Fire	0	0	3	0.7	3	1.1
Surface Water & Ground Water	2	5.3	0	0	0	0

Total	38	100	406	100	268	100
<i>Fate of N Emissions</i>						
N deposition in California	0	0	135	33.3	67	25.0
Export to atmosphere or beyond California	38	100	270	66.7	201	75.0

902

903

904

905

906

907

908

909

910

911

912

913

914

915

DRAFT: Stakeholder Review

916 **Table 5.4.5 Default values and uncertainty range for IPCC emission factors used to calculate direct and indirect N₂O emissions from**
 917 **agricultural soils in the California Greenhouse Gas Emissions Inventory.** Sources: IPCC 2006; CARB 2009. [\[Return to text\]](#)

Category	Emission Factor Description	Default Value	Uncertainty Range
Direct N ₂ O emissions	Proportion of N applied to soils via synthetic fertilizer, organic fertilizer, manure, N-fixing crops that is emitted as N ₂ O	0.01	0.003 - 0.03
	Proportion of N deposited by livestock on pastures, rangeland, and paddocks that is emitted as N ₂ O	0.02	0.007 - 0.06
	N emitted as N ₂ O per unit area of cultivated organic soils (kg N per ha)	8	2-24
Indirect N ₂ O emissions	Fraction of synthetic fertilizer N that volatilizes	0.1	0.03 - 0.3
	Fraction of organic fertilizer and manure N that volatilizes	0.2	0.05 - 0.5
	Leaching rate: Fraction of applied N lost to leaching and runoff	0.3	0.1 - 0.8
	Proportion of N volatilized and re-deposited on soils that is emitted as N ₂ O	0.01	0.002 - 0.05
	Proportion of N lost to leaching and runoff that is emitted as N ₂ O	0.0075	0.0005 -0.025

918

919

920