Chapter 5: Ecosystem services and human well-being

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**Main Messages**

Human activities that increase reactive N have numerous competing effects on the ecosystem and biogeochemical processes that regulate the Earth’s climate. Some processes have net warming effects.
that exacerbate climate change, while other processes have net cooling effects that partially offset the prevailing trend of a warming climate.

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

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

The formation of O₃ from NOₓ has both warming and cooling effects on the earth’s climate. Increased ground-level O₃ has adverse effects on plant photosynthesis and CO₂ uptake, which decrease C sequestration by crops and natural vegetation. While estimates suggest that O₃ decreases plant C sequestration by 14 -23% globally, more research is needed to quantify the extent of this impact in California. In contrast, O₃ can also have a small cooling effect on climate by increasing the concentration of hydroxyl radicals (OH), which in turn reduce the lifetime and overall burden of CH₄ in the atmosphere.
Atmospheric aerosols formed from NO$_x$ and NH$_3$ have a short term cooling effect on climate by reflecting and scattering solar radiation and stimulating cloud formation and the albedo effect. Since the formation of aerosols from NO$_x$ and NH$_3$ are generally linked to different pollution sources (e.g., fossil fuel $\rightarrow$ NO$_x$, livestock $\rightarrow$ NH$_3$), the relative contribution of each pollutant and the chemical composition of resulting aerosols is likely to vary considerably across California’s landscape.

Estimates suggest that anthropogenic sources of N have a modest net-cooling effect on the Earth’s climate in the near-term (20 yr), but a net warming effect in the long-term (100 yr) as the prolonged effects of N$_2$O dominate the radiative balance. It should also be noted that the overall effects of N on the climate are relatively small compared to CO$_2$ from fossil fuel combustion (8% globally, 3-4% in California).

5.4 Climate regulation

5.4.0 Introduction

Nitrogen plays a well-established role in regulating the Earth’s climate. Human activities that increase the amount of reactive N that enters terrestrial and aquatic ecosystems can alter many biogeochemical processes that affect the Earth’s climate balance (Figure 5.4.1). Most notably, increases in reactive N can change the emission and uptake of the three important greenhouse gases: carbon dioxide (CO$_2$), methane (CH$_4$), and nitrous oxide (N$_2$O). Emissions of N oxides (NO$_x$) and NH$_3$ also have important impacts on climate, since they are chemical precursors to ozone (O$_3$) and various atmospheric aerosols [Box 5.4.1]. The ecosystem processes and atmospheric feedbacks involving N are complex, and thus the magnitude of their effects on the global climate are often uncertain. In this section, we examine the
effects of reactive N on the Earth’s climate balance paying particular attention to California’s contribution to climate change over time through human activities and ecosystem processes that effect global N and carbon (C) cycles.

[Figure 5.4.1]

[Box 5.4.1]

5.4.1 Measures of the radiative forcing and global climate change

Several important metrics are used to quantify the effects of ecosystem processes that regulate the Earth’s climate. The two most commonly used measures are radiative forcing (RF) and global warming potential (GWP). Radiative forcing is a measure of the influence that a factor (e.g., greenhouse gas, atmospheric aerosol) has in changing the balance of energy in the atmospheric system and is expressed in Watts per square meter (W m⁻²) of the Earth’s surface. More specifically, the Intergovernmental Panel on Climate Change (IPCC) calculates RF as the change in W m⁻² relative to preindustrial conditions (i.e., pre-1750) (IPCC 2007). The amount of heat trapped by a particular gas depends on its absorption of infrared radiation, the absorption wavelength and the atmospheric lifetime of the gas species (IPCC 2007). By integrating the RF caused by a 1kg pulse of given gas over a standard time period (20 yr, 100 yr, 500 yr) its absolute global warming potential (also expressed in W m⁻²) can be calculated. While the IPCC uses the GWP over a 100yr time period in its policy frameworks, the shorter and longer time frames have also proven useful for detailed modeling studies (IPCC 2001; Shine 2007). Another convention adopted by the IPCC is to express the GWP of a gas relative to an equivalent mass of CO₂ (IPCC 2007). As such, CO₂ is standardized to a GWP value of 1 and other gases are expressed in terms of carbon dioxide equivalents (CO₂e) integrated over a 100yr time period. For example, the GWP of one kg of N₂O over 100 years is 298 kg CO₂e (Table 5.4.1; IPCC 2007). Due to its computational simplicity, GWP
has been widely adopted by scientists and policy makers working under the IPCC framework. More recent work by Shine et al (2005; 2007) has introduced the global temperature potential (GTP) as an additional measure for consideration by the IPCC. The GTP is calculated as the ratio between the global mean surface temperature change (change in degrees K per kg\(^{-1}\) gas) at a given future time point following a pulse or sustained emission of a gas relative to CO\(_2\) (Shine et al. 2005). Since both GWP and GTP are measures of radiative forcing relative to CO\(_2\), they share many advantages as metrics useful for policy making. The main difference between GWP and GTP is that while the GWP integrates the temperature change over a standard time period (i.e., the contribution of the RF at the beginning and end of the time horizon is exactly equal) the GTP calculates the actual temperature change between the time emitted and a precise future end point (i.e., the RF closer to the end point contributes relatively more) (Shine et al. 2005). While GTP has yet to gain widespread usage by the IPCC, several recent studies by the US Environmental Protection Agency have employed this metric to assess the overall impacts of reactive N species on both short- and long-term changes in climate (Pinder et al. 2012a; Pinder et al. 2012b).

5.4.2 Effects of reactive N on the global climate

It is well-established that while some human activities involving reactive N result in warming effects that can amplify climate change, others lead to cooling effects that minimize or offset the prevailing global warming trend (Figure 5.4.2; Erisman 2011; Pinder 2012a; Pinder 2012b). For example, emissions of N\(_2\)O have a strong long-term warming effect due to the atmospheric lifetime of the gas and its high GWP (Table 5.4.2; Parry et al. 2007; Smith et al. 2007). In contrast, sequestration of C by natural vegetation caused by increased N deposition typically has a long-term cooling effect on climate (Table [Table 5.4.1])
5.4.2. The effects of atmospheric aerosols also tend to cool the climate, but since they only remain in
the atmosphere for a short time period (hours-weeks) their effects are limited in duration (Table 5.4.2;

While there is considerable uncertainty in estimating the magnitude of these countervailing
processes, several recent studies have developed methods for quantifying the net effects of reactive N
on the global climate (Figure 5.4.2). Principal among these is a study by Erisman et al. (2011) which
concluded that reactive N has an overall net cooling effect on RF for the Earth’s present climate (-0.24
W m\(^{-2}\)), albeit with a wide uncertainty range (-0.5 to +0.2 to W m\(^{-2}\)) (Figure 5.4.3). Using the same
methodology, Butterbach-Bahl et al. (2011) also found a net cooling effect of anthropogenic N from
European sources on global RF. In contrast, Pinder et al. (2012a, 2012b) used an alternative method to
calculate the change in GTP due to reactive N sources in the United States over time. Consistent with
previous work they also found a modest cooling effect of reactive N in the near-term (20 yr) due mostly
to the short-lived effects of O\(_3\) and N-derived aerosols, but indicated that warming will likely occur in
the longer-term (100 yr) when the prolonged effects of N\(_2\)O dominate the radiative balance (Figure
5.4.4). However, it should also be noted that the net effects of N on climate are very small compared to
CO\(_2\) from fossil fuel combustion. Thus, the modest cooling effect of reactive N in the near-term is
thought to provide only a slight offset to the significant warming trend that is driven mostly by global
CO\(_2\) emissions (Figure 5.4.5).
Thus far, the results of these global and national studies have not been down-scaled or disaggregated for California. However, the convergence of evidence indicates that the climate forcing effects of reactive N in California are likely similar to those observed in the US and Europe. While a full radiative balance for reactive N in California is beyond the scope of this analysis, the following sections summarize the existing data and knowledge on the main N-related processes in California that influence climate change in both the short and long term.

5.4.3 Effects of reactive N on N$_2$O emissions

As indicated above, emissions of N$_2$O have a long-term warming effect on the global climate that is well-established in the scientific literature (Figure 5.4.2; Ramaswamy et al. 2007). The primary biochemical mechanisms that produce N$_2$O are nitrification and denitrification, which are mediated by aerobic nitrifying bacteria and anaerobic denitrifying bacteria (Figure 5.4.1). Recent estimates suggest that approximately 57 - 62% of global N$_2$O emissions come from natural sources (10.5-11 Tg N yr$^{-1}$), with the remaining 38 - 43% attributed to anthropogenic sources (6.7 - 7.8 Tg N yr$^{-1}$) (Forster et al. 2007; Syakila and Kroeze 2011). Furthermore, human efforts to fix atmospheric N into usable reactive forms through the Haber-Bosch process and the cultivation of N$_2$-fixing crops have increased N$_2$O concentrations in the atmosphere by about 16% relative to pre-industrial times (Forster et al. 2007; Park et al. 2012). Emissions of N$_2$O come from multiple anthropogenic sources including N fertilizers, N$_2$-fixing crops, livestock urine and manure, sewage and wastewater, biomass burning, and fossil fuel combustion (Parry et al. 2007; Smith et al. 2007). Terrestrial and aquatic ecosystems are also sources of non-anthropogenic N$_2$O emissions, but significant losses of N from anthropogenic sources to natural and semi-natural ecosystems (e.g., via NO$_3$ leaching, NH$_3$ volatilization, NO$_x$ emissions, N deposition) make it difficult to accurately determine whether a molecule of reactive N originates from natural or human fixation.
Globally N$_2$O accounts for about 8% of total anthropogenic GHG emissions if all are expressed in CO$_2$e, making it the third most important GHG behind CO$_2$ (77%) and CH$_4$ (14%) (Figure 5.4.6; IPCC 2007; Smith et al. 2007). In California, a relatively small fraction (3-4%) of the state’s total GHG emissions are attributed to N$_2$O, and these emissions have remained at a relatively stable level between 1990 and 2009 (Table 5.4.3; Figure 5.4.2; CARB 2010). This stable trend for N$_2$O has also been observed nationally and has been attributed to widespread adoption of catalytic converters in recent decades (which reduce both NO$_x$ and N$_2$O) and has off-set small increases in N$_2$O from fertilizer consumption.

During the 1990s and 2000s, N$_2$O emissions on the order of 15-16 MT CO$_2$e were emitted in California each year, with 68% of N$_2$O emissions coming from agriculture (Table 5.4.3; Table 5.4.4). The remaining N$_2$O emissions in California come from sewage treatment (7%) and fossil fuel combustion in the transportation, energy, and industrial sectors (24%) (Table 5.4.4).

**Emissions of N$_2$O from California agriculture**

Despite N$_2$O being a small fraction of the state’s overall GHG emissions, between 30 and 40% of the emissions attributed to agriculture in California come from N$_2$O emissions (CARB 2010; Haden et al. 2012). California’s state-wide estimates for the various agricultural sources of N$_2$O are based on emissions inventory guidelines developed by the Intergovernmental Panel on Climate Change (IPCC 2006). The IPCC’s Tier 1 methods use default emission factors (EFs) derived from a “bottom-up” assessment of field experiments covering a wide range of global crops, environments, water management regimes, N sources and nutrient management practices (Bouwman et al. 2002a; Bouwman...
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
bottom-up accounting frameworks for agricultural emissions referred to above (Box 5.4.2). In the Crutzen et al. (2008) study, which uses a N budget approach informed by data on the size of global N sources and sinks and the known rate of N$_2$O accumulation in the atmosphere, approximately 3-5% of newly fixed N is ultimately emitted as N$_2$O. Building on this approach, Smith et al. (2012) found a good fit between observed atmospheric N$_2$O concentrations from 1860 to 2000 and estimates of N$_2$O emissions based on a 4% EF by using estimates of reactive N entering the agricultural cycle that account for both mineralization of soil organic N following land use change and NOx deposited from the atmosphere. In the approach used by Davidson (2009), they assume that N molecules in the fertilizer used to produce animal feed are later recycled in manure applied to soil. The results of their analysis indicate that approximately 2% of N in manure and 2.5 % of N in fertilizer is eventually converted to N$_2$O. It is important to note that while these top-down methods indicate 2-3 fold higher N$_2$O emissions than the IPCC’s Tier 1 approach, the contribution of N$_2$O to California’s total GHG emissions (< 5-10%) is still relatively minor compared to CO$_2$. These recent studies also highlight the fact that while the IPCC default EFs provide a computationally simple way to estimate N$_2$O emissions, the high degree of uncertainty can restrict the precision of national and regional inventory estimates (Smith et al.2010).

In an effort to improve estimates of N$_2$O emissions from California agriculture, state agencies (e.g. California Energy Commission, California Air Resources Board) have commissioned a number of recent field studies to measure emissions for California cropping systems with goals of 1) calibrating and validating soil biogeochemical models (e.g., DAYCENT Model, Denitrification-Decomposition Model), 2) assessing the impact of alternative agricultural practices (De Gryze et al. 2009; De Gryze et al. 2010; Horwath and Burger 2012; Burger et al. 2005). As a case in point, Horwath and Burger (2012) recently published a report of California-based field studies measuring N$_2$O emissions in tomato, wheat, alfalfa, and rice cropping systems. They found that cumulative N$_2$O emissions from furrow-irrigated tomatoes...
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, they obtained EFs ranging from 0.24 to 0.98% of applied N (Horwath and Burger 2012), results that were consistently lower than the well-established 1% IPCC default EF and the 1.21% mean EF derived from 25 global wheat studies (Linquist et al 2012). Horwath and Burger (2012) also found that EFs for alfalfa, a N-fixing crop, ranged from 4.5% in a 1 year old stand to 12.06 % in an adjacent 5 year old stand. The annual N₂O emissions measured in rice systems ranged from 0.26 to 0.85 kg N₂O-N ha⁻¹ and EFs between 0.12 and 0.74% and were similar to the mean EF estimated in a recent meta-analysis of 17 other rice experiments conducted globally (Horwath and Burger 2012; Linquist et al, 2012). While a few studies have also begun to examine N₂O emissions in California orchards and vineyards, more experimental data are needed to validate biogeochemical models for the state’s diverse perennial and annual cropping systems (Steenworth and Balina 2010; Smart et al. 2011; Suddick et al. 2011).

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

As with agricultural soils, the N₂O emissions that arise from sewage and wastewater treatment facilities are associated with the breakdown and mineralization of N compounds present in the wastewater and effluent. Again, nitrification and denitrification are the main mechanisms driving N₂O emissions. In general, the N₂O emissions occurring directly within the treatment facilities are relatively small compared to the effluent that is discharged into surface water bodies. Overall, sewage and wastewater treatment account for approximately 7% of California’s N₂O emissions (Table 5.4.4). In addition to significant amounts of CO₂, the burning of fossil fuels also produces N₂O and accounts for approximately 24% of California’s N₂O emissions (Table 5.4.4). In the industrial sector, the production of nitric acid via the oxidation of NH₃ and the application of concentrated nitric acid as an oxidizer for production of
various chemicals both result in N$_2$O emissions. In California, N$_2$O emissions from nitric acid production in California are small and have declined from 535,000 MT CO$_2$e in 1990 to less than 200,000 MT of CO$_2$e in 2008 (CARB 2010). Together, N$_2$O emissions from wastewater treatment, fossil fuel combustion and nitric acid production amount to less than 1% of California’s total anthropogenic GHG emissions, which is dominated mostly by CO$_2$ and to a lesser extent CH$_4$ (CARB 2010).

5.4.4 Effects of reactive N on biosphere C stocks and the efflux of CO$_2$ and CH$_4$

Effects of N on terrestrial C Sequestration

One of the most prominent cooling effects of reactive N is its stimulation of plant growth in terrestrial ecosystems, which removes CO$_2$ from the atmosphere and sequesters C in plant biomass (Butterbach-Bahl et al. 2011; Pinder et al. 2012a). It is well-established that the net primary productivity (NPP) of most ecosystems is limited by the availability of N (Figure 5.4.1; LeBauer and Treseder 2008). Consequently, estimates suggest that N deposition in temperate North American forests increases above- and below-ground C stocks by 24 - 177 kg C per kg N deposited per year (Sutton et al. 2008; Liu and Greaver 2009; De Vries et al. 2009; Thomas et al. 2010). While generally lesser in magnitude, N deposition also increases C sequestration in the vegetation of temperate grasslands and wetlands (LeBauer and Treseder 2008).

Soils are an even larger sink for carbon, with 2-3 times more C stored in soils than in vegetation globally (White et al. 1999). Most evidence from forest ecosystems suggests that sequestration of C in soil increases with higher rates of N deposition (Fenn et al. 1996). In agroecosystems, the application of N fertilizers and manure can also build soil C stocks (Ladha et al. 2011; Pinder et al. 2012a). The main mechanisms responsible for N-induced C storage in soil are greater inputs of organic matter through leaf
litter, crop residues, decreased rates of litter decomposition, and decreased soil respiration (Knorr et al. 2005; Janssens et al. 2010).

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

In some cases, excessive N inputs can lead to “N saturation” where the negative effects of soil acidification, base-cation leaching, aluminum toxicity, and Fe immobilization are thought to overwhelm the positive effects of N fertilization, ultimately leading to forest decline and loss of stored C (Aber et al. 1989; Matson et al. 2002; Bowman et al. 2008). The adverse effects of excess N are also likely to differ among plant species and ecosystems. Instances of N saturation have been reported in the forests of California’s San Bernardino Mountains, though measurable losses of C from forest decline were not observed in this case (Fenn et al. 1996). Furthermore, these authors hypothesize that the high base saturation of arid forest soils in the Western US make decline less likely than in other forest ecosystems (Fenn et al. 2003). While more long-term research is needed to determine if N saturation from continued air pollution will eventually lead to losses of stored C, it is provisionally agreed upon by most
that inputs of reactive N generally have a positive effect on C sequestration in California’s ecosystems (Figure 5.4.2). That said, it is important to note that plant biomass and soils are not permanent sinks for carbon and a significant fraction of the carbon will eventually be returned to the atmosphere due following plant death, harvest, decomposition, and wild-fire. Future research conducted in California is therefore critically important, not just to understand the N response from different ecosystems and plant species, but also to determine the time-scales of carbon storage and loss to the atmosphere.

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

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

Liu and Greaver (2009) carried out a meta-analysis of existing studies which found that N addition via fertilization and deposition increased in CH₄ production by 95% and decreased CH₄ oxidation by 38% when averaged across grassland, wetland and anaerobic agricultural systems. However, when each ecosystem type was analyzed separately the effect of N addition on both CH₄ production and CH₄ oxidation was only significant in anaerobic agricultural fields. When combined, these processes result in more total CH₄ entering the atmosphere, albeit only a very small amount more
since agricultural soils tend to be weak sinks. Consequently, when Liu and Greaves estimates were used in recent studies the overall warming effect of N on net CH$_4$ emissions occurring in anaerobic agricultural fields was found to be virtually negligible at both the US national scale (Figure 5.4.4; Pinder et al. 2012) and the global scale (Figure 5.4.5; Erisman et al. 2011). At present, no studies have quantified the overall effect of reactive N on CH$_4$ emissions in California. However, it is reasonable to assume that the universal biochemical processes that govern CH$_4$ emissions in soils will yield results in California that are similar to those observed in other wetland, forest, grassland and agricultural ecosystems (Figure 5.4.2).

5.4.5 Effects of reactive N on atmospheric gases and aerosols

Effects of N and O$_3$ on ecosystems and the atmosphere

As discussed in Chapter 5.3, emissions of NO$_x$ and NH$_3$ have a multitude of effects on the chemistry of atmospheric gases and the formation of O$_3$ and aerosols, many of which have important implications for the Earth’s climate. Most importantly, NO$_x$ and volatile organic compounds play a role in the formation of tropospheric O$_3$, which has a warming effect on the climate (Pinder et al. 2012a) through its adverse effects on plant photosynthesis and CO$_2$ uptake (Felzer et al. 2004; Pan et al. 2009; Arneth et al. 2010; See Chapter 5.3). The damaging effects of tropospheric O$_3$ on plant growth are estimated to decrease the ability of the world’s vegetation to sequester atmospheric CO$_2$ by as much as 14-23% (Figure 5.4.4; Sitch et al. 2007; Pinder et al. 2012b). While NO$_x$ and O$_3$ concentrations throughout much of California have been declining since the 1970s (See Figures 5.3.3 and 5.3.6), O$_3$ levels during the spring and summer months are still among the highest in the United States (Felzer et al. 2004). Experimental and modeling studies indicate that sensitivity to tropospheric O$_3$ is generally highest for crops followed by deciduous vegetation, with coniferous vegetation generally more tolerant (Felzer et al. 2004; Shrestha...
and Grantz 2005; Grantz and Shrestha 2006). Recent studies by Felzer et al. (2004, 2005) suggest that in
despite of high O₃ levels the overall effect on C storage in Southwestern ecosystems (inclusive of
California) is lower than in the Midwestern and Southeastern regions of the United States. This result is
due mainly to California’s arid summer climate which constrains net primary productivity and thus the
total amount of C sequestered by native vegetation. While these studies are inclusive of California, no
focused efforts have been made to quantify the impact of O₃ on statewide C sequestration.

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

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

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

The chemical complexity of atmospheric aerosols and the paucity of empirical data on their effects results in a high level of uncertainty regarding the magnitude and duration of their impact on the Earth’s radiative balance (Figure 5.4.5; Ramaswamy et al. 2007). Globally, aerosols derived from NOₓ and NH₃ are together estimated to have a radiative forcing of -0.38 W m⁻², with the negative value indicative of a modest cooling effect on the present climate (Shindell et al. 2009; Erisman et al. 2011). For the US, Pinder et al. (2012a) found a similar cooling effect of N-derived aerosols in the near term (20 yr), but considered their long-term impact on climate to be negligible relative to CO₂, CH₄, and N₂O emissions and terrestrial C sequestration (Figure 5.4.4). Recent studies also suggest that the short term cooling effect of NOₓ-derived aerosols are 2 to 4 times as large as the effect of NH₃-derived aerosols (Shindell et
al. 2009; Pinder et al., 2012a). However, since the formation of aerosols from NO$_x$ and NH$_3$ are generally linked to different pollution sources (e.g., fossil fuel $\rightarrow$ NO$_x$, livestock $\rightarrow$ NH$_3$) the relative contribution of each pollutant is likely to vary considerably across California’s landscape (See Chapter 5.3). For example, recent studies indicate that in the San Joaquin Valley, where fossil fuel combustion and agricultural activities produce a balanced mix of NO$_x$ and NH$_3$, NH$_4$NO$_3$ tends to be the most abundant chemical species among atmospheric aerosols (Battye et al. 2003). In parts of California where NH$_3$ emissions are low, NH$_4$NO$_3$ is a much more minor component of aerosols. At present, only a small number of studies have tried to quantify California’s total contribution of NO$_x$ and NH$_3$ derived aerosols to the atmosphere, and no available statewide studies are known to have estimated their net effects on global climate change.

5.4.6 Future research needs in California

The recent efforts to quantify the short and long term climate impacts of reactive N at the national and global scales have established sound methodologies for understanding the anthropogenic sources and environmental fate of various forms of reactive N, as well as their relative contribution to climate change (Erisman et al. 2011; Butterbach-Bahl et al. 2011; Pinder et al. 2012a; Pinder et al. 2012b). Across these regional scales, it is provisionally agreed upon by most that the modest cooling effect of reactive N in the near-term is likely to be short-lived as increasing concentrations of N$_2$O build up in the atmosphere and exacerbate the overall warming trend driven primarily by CO$_2$ (Figure 5.4.2).

While California’s contribution to Earth’s radiative balance has not been fully assessed in the scientific literature, it is likely that the sources of N, climate forcing processes and overall trends will be similar to those reported in the large-scale regional assessments discussed above. That said, future studies are still needed to confirm whether or not this is true for California in particular. For those
interested in pursuing a more comprehensive statewide analysis, the data presented in the preceding
mass-balance on key flows of reactive N (e.g., N₂O, NOₓ, and NH₃ emissions; N deposition) may serve
as a useful starting point for future studies (See Chapter 4; Table 5.4.4). With an eye towards future
research, the following studies would be needed to complete a full assessment of California’s
contribution to climate change through anthropogenic sources of reactive N.

- Field and modeling studies measuring N₂O emissions from California’s diverse annual and
  perennial cropping systems. These are needed to improve the calibration of soil biogeochemical
  models and thus reduce the uncertainty of statewide N₂O emissions estimates.
- Ecological studies quantifying the effects of N deposition on both C sequestration and CH₄
  emissions in California’s natural and agricultural ecosystems.
- Ecological and atmospheric studies quantifying the effects of tropospheric O₃ on C
  sequestration by native vegetation and crops in California.
- Atmospheric studies evaluating the effects of NOₓ emitted in California on the formation of O₃,
  hydroxyl radicals and the decay of CH₄.
- Atmospheric studies quantifying the radiative effects of aerosols formed from emissions of NOₓ
  and NH₄ in California.
References


**Carlsson-Kanyama, A. 1998.** Climate change and dietary choices - how can emissions of greenhouse gases from food consumption by reduced? *Food Policy* 23(3/4): 277-293.


IPCC (Intergovernmental Panel on Climate Change) 2001 Climate change 2001: the scientific basis. Intergovernmental Panel on Climate Change. Cambridge, UK: Cambridge University Press.


Nitrous oxide (N$_2$O) contributes to two distinct global environmental issues: climate change and stratospheric ozone depletion. As a greenhouse gas, N$_2$O is 298 times more potent than carbon dioxide and is the third most abundantly emitted greenhouse gas (after carbon dioxide and methane) (Forster et al. 2007). Overall, N$_2$O is responsible for approximately 8% of the global anthropogenic greenhouse gas emissions that contribute to climate change (Forster et al. 2007). While N$_2$O is a relatively long-lived greenhouse gas, in the stratosphere solar radiation eventually degrades the molecule to form the free radical nitric oxide (NO) which has additional implications for the separate issue of ozone depletion. Free radicals such as NO catalyze secondary reactions that convert ozone (O$_3$) and a single oxygen atom (O) into two molecules of oxygen gas (O$_2$) (e.g., O + O$_3$ $\rightarrow$ 2 O$_2$). Consequently, increased N$_2$O emissions also ultimately lead to a buildup of NO in the stratosphere, the depletion of the Earth’s ozone layer and the subsequent loss of protection from the sun’s ultraviolet light. At present, N$_2$O is the most abundantly emitted ozone depleting substance, and will be for the remainder of the 21st century if emissions continue at their current pace (Ravishankara et al. 2009).

N$_2$O is not the only substance to have these dual properties. Many ozone depleting substances, including chlorofluorocarbons (CFCs), methyl bromide and several other gas species are also highly potent greenhouse gases. And yet N$_2$O and CFCs are controlled under two different treaties: CFCs under the 1987 Montreal Protocol and N$_2$O under the 1997 Kyoto Protocol. The Montreal Protocol is considered a model of global environmental cooperation. Under the Montreal framework, the production and commercial use of ozone depleting substances (with the notable exception of N$_2$O) have been reduced by approximately 97% globally (Velders et al. 2007). This success in reducing the emissions...
of other ozone depleting substances is the main reason that $\text{N}_2\text{O}$ is now the dominant remaining ozone depleting substance. In contrast, the Kyoto Protocol significantly undershot its first phase targets and the parameters of its second commitment period (with a diminished membership) remain unclear. Kyoto’s uneven track record has motivated some to explore how the Montreal Protocol might be expanded to include $\text{N}_2\text{O}$ and thus maximize the dual ozone and climate benefits of the existing policy framework (Kanter et al. 2013).

In California, the use of N fertilizers and livestock manure in agriculture are the largest sources of anthropogenic $\text{N}_2\text{O}$ emissions. Other sources of $\text{N}_2\text{O}$ include fossil fuel combustion, nitric and adipic acid production, biomass burning and wastewater. Chapters 7 and 8 of this assessment evaluate a range of technical and policy strategies for mitigating $\text{N}_2\text{O}$ emissions from these economic sectors. Practices to improve fertilizer use efficiency by optimizing N rates, split applications, controlled release fertilizers, nitrification inhibitors, fertigation technologies and other types of precision agriculture have the potential to reduce $\text{N}_2\text{O}$ emissions without adverse effects on crop yields (Robertson and Vitousek 2009). In particular, a recent review of 35 studies found that nitrification inhibitors and controlled release fertilizers on average can reduce $\text{N}_2\text{O}$ emissions by approximately 38% and 35% respectively (Akiyama et al. 2009) and are steadily increasing their market share (USDA ERS 2012). Considerable progress has also been made with the adoption of catalytic conversion for both stationary and mobile combustion sources and in the processes used for nitric acid production, with the added benefit of also often reducing NO$_x$ emissions (Wiesen 2010). Likewise, any of the agricultural strategies for reducing $\text{N}_2\text{O}$ are also likely to have positive environmental co-benefits by reducing other forms of nitrogen pollution that diminish California’s water and air quality.
Box 5.4.2 Climate impacts of fertilizer manufacture [Return to text]

Use of synthetic nitrogen fertilizer typically accounts for a high percentage of greenhouse gas (GHG) emissions in conventional crop production. In addition to soil emissions resulting from the application of fertilizers on crop fields, the production of the fertilizer itself accounts for a large portion of total emissions. According to a selection of food life cycle assessment studies (Carlsson-Kanyama 1998; Blengini and Busto 2009), the proportion of total GHG emissions attributable to fertilizer production can range from less than 5% to 18%, depending on the type of food product being analyzed and the system boundaries of the study. For some horticultural crops, it can account for up to 70% of CO$_2$ emissions (not counting other GHGs) up to farmgate (Lillywhite et al. 2007). Moreover, fertilizer production has been estimated to account for 1.2% of the world's total energy use and 1.2% of the total GHG emissions (Kongshaug 1998).

Nitrogenous fertilizer production relies on the Haber-Bosch process, an industrial process that synthesizes ammonia (NH$_3$) by mixing nitrogen from the air with hydrogen under high temperature and pressure conditions, requiring a large amount of energy - approximately 25-35 GJ/tonne NH$_3$ (DOE 2000). Approximately 80% of the world's NH$_3$ production uses natural gas as both the hydrocarbon feedstock (as the source of hydrogen) and as the energy source, resulting in CO$_2$ emissions as the dominant component of GHG emissions (Wood and Cowie 2004). Various studies have estimated emissions in NH$_3$ production to range from 1150 to 2800 g CO$_2$-equivalent (CO$_2$-e) per kg NH$_3$, or 1402 to 3415 g CO$_2$-e per kg N content (Wood and Cowie 2004, PE International 2009). Wood and Cowie (2004) report that the transparency of reviewed reports was inadequate to explain these large differences between estimates, but that a large portion of the variation is likely due to variation in plant efficiencies, the use of alternative fossil fuels, and differences in methods for accounting for the steam
exports that result from the process (which can be used for electricity generation and therefore can be
counted as a credit toward the fertilizer emissions, due to offsetting of other electricity generation). A
study commissioned by Natural Resources Canada (2007) confirms that measures taken by Canadian
urea production plants to improve overall energy efficiency and re-use CO₂ (see below) result in
substantially lower emissions relative to facilities in other parts of the world.

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

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

For perspective, we can calculate rough estimates for CO₂-equivalent soil emissions resulting
from application of these fertilizer products to agricultural fields. The IPCC default emissions factor for
direct \( \text{N}_2\text{O} \) emissions (the emissions resulting from direct nitrification and denitrification pathways for fertilizer N) is 1% of applied N (IPCC 2006, p 11.11). In the case of NH\(_3\), which is 82% N by mass, the emissions would thus be estimated as 8.2 g \( \text{N}_2\text{O} \) per kg ammonia (calculated as 1% of 820 g NH\(_3\)-N). This figure translates to 12.89 g \( \text{N}_2\text{O} \), and 3816 g CO\(_2\)-e per kg product, or 4654 g CO\(_2\)-e per kg N applied (using the 100-yr global warming potential of 296 for \( \text{N}_2\text{O} \)). One should note that these calculations do not include indirect emissions - those arising from volatilization, leaching, and runoff of fertilizer N, some of which later becomes \( \text{N}_2\text{O} \) in off-site locations. As with direct emissions, these processes can vary tremendously according to soil type, climate, and management practices, but the default factors suggested by IPCC (2006) for use when these specific variables are unknown, would raise the total emissions estimates by an additional 33%. At any rate, the GHG emissions produced in manufacture of the fertilizer range from 20 to 150% of emissions produced after field application, or 23 to 60% of total emissions attributable to N fertilizer use, depending on fertilizer product, manufacturing efficiency, and additional variables. Given that many field studies have found that field emissions in specific locations and conditions may in fact be much lower than the IPCC default factors (Snyder et al. 2009), the proportion of life cycle GHG emissions attributable to fertilizer production may be correspondingly higher. Nitrogenous fertilizer production, therefore, contributes substantially to total climate change impacts of synthetic fertilizer use.
Figure 5.4.1 Potential mechanisms regulating the terrestrial ecosystem responses of CO₂, CH₄ and N₂O production and consumption to increased availability of reactive N. ANPP = aboveground net primary productivity; BNPP = belowground net primary productivity; SOC = soil organic carbon; DOC = dissolved organic carbon; DIN = dissolved inorganic nitrogen; DON = dissolved organic nitrogen. Source: Liu and Greaver 2009. [Return to text]
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 agreement for the various nitrogen-related biogeochemical processes that influence climate regulation over time. [Return to text]

<table>
<thead>
<tr>
<th>Low agreement</th>
<th>Medium agreement</th>
<th>High agreement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low evidence</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low agreement</td>
<td>Aerosols formed from nitrogen oxides and ammonia reflect solar radiation leading to short-term cooling effects</td>
<td></td>
</tr>
<tr>
<td>Medium evidence</td>
<td>Anthropogenic nitrogen has a cooling effect on climate in the near-term (20yr), but a net warming effect in the long term</td>
<td>Nitrogen deposition increases the flux of methane from anaerobic soils leading to a net warming effect on climate</td>
</tr>
<tr>
<td>High evidence</td>
<td>Nitrous oxide emissions, mostly from agriculture, account for about 3% of CA’s total GHG emissions</td>
<td>Ground-level ozone has adverse effects on plant carbon sequestration which lead to a net warming effect on climate</td>
</tr>
<tr>
<td></td>
<td>Terrestrial carbon sequestration stimulated by N deposition has a net cooling effect on climate</td>
<td>Stratospheric ozone increases the hydroxyl radicals and reduces the atmospheric lifetime methane, which have a cooling effect on climate</td>
</tr>
<tr>
<td></td>
<td>Nitrous oxide emissions have a long-term net warming effect on the climate</td>
<td>Human activities that increase reactive nitrogen in the environment have a mix of competing warming and cooling effects on climate</td>
</tr>
</tbody>
</table>
Figure 5.4.3 Influence of anthropogenic reactive N on global radiative forcing on the present climate. Radiative forcing values above zero imply a warming effect on the present global climate, while negative values indicate a cooling effect. “N x C Sequestration” includes effects of N deposition on C sequestration and CO₂ efflux in terrestrial and aquatic systems and mineralization in soil. “NOₓ emissions” contains effects of O₃ and other aerosols formed from reactions with NOₓ. “NH₃ emissions” are particulates and other aerosols formed from NH₃ in the atmosphere. “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 NOₓ 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 et al. 2009 [Return to text]
Influence of Reactive N on Global Radiative Forcing

Radiative Forcing (W m$^{-2}$)

- N$_2$O Emissions
- N x C Sequestration
- NOx Emissions
- NH3 Emissions
- O3 Phytotoxicity
- CH4 Emissions
- Total
Figure 5.4.4 The climate change impacts of US reactive nitrogen emissions from combustion and agriculture, in common units of equivalent Tg of CO$_2$ (Tg CO$_2$e) on a 20-year and 100-year global temperature potential (GTP) basis. The width of the bar denotes the uncertainty range; the white line is the best-estimate; and the color shading shows the relative contribution of combustion and agriculture. Source: Pinder et al. 2012a. [Return to text]
Figure 5.4.5 Global mean radiative forcings (RF) and their 90% confidence intervals in 2007 for various agents and mechanisms (a) and probability distribution of the global mean combined radiative forcing from all anthropogenic agents shown in (b). Columns on the right-hand side indicate best estimates and confidence intervals (RF values); typical geographical extent of the forcing (Spatial scale); and level of scientific understanding (LOSU). Errors for CH₄, N₂O and halocarbons have been combined. The net anthropogenic radiative forcing and its range are also shown. Best estimates and uncertainty ranges can not be obtained by direct addition of individual terms due to the asymmetric uncertainty ranges for some factors; the values given here were obtained from a Monte Carlo technique. Additional forcing factors not included here are considered to have a very low LOSU. Volcanic aerosols contribute an additional form of natural forcing but are not included due to their episodic nature. The range for linear contrails does not include other possible effects of aviation on cloudiness. The distribution is calculated by combining the best estimates and uncertainties of each component. The spread in the distribution is increased significantly by the negative forcing terms, which have larger uncertainties than the positive terms. Source: IPCC 2007. [Return to text]
### Table: RF Terms and Values

<table>
<thead>
<tr>
<th>RF Terms</th>
<th>RF Values (W m(^{-2}))</th>
<th>Spatial scale</th>
<th>LOSU</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Anthropogenic</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Long-lived greenhouse gases</td>
<td>0.04 (0.43 to 0.63)</td>
<td>Global</td>
<td>High</td>
</tr>
<tr>
<td>Stratospheric ozone</td>
<td>0.33 (0.31 to 0.37)</td>
<td>Global</td>
<td>High</td>
</tr>
<tr>
<td>Stratospheric water vapour from CH(_4)</td>
<td>0.07 (0.02 to 0.12)</td>
<td>Global</td>
<td>Low</td>
</tr>
<tr>
<td>Surface albedo</td>
<td>-0.05 [-0.15 to 0.05]</td>
<td>Continental to global</td>
<td>Med</td>
</tr>
<tr>
<td>Direct effect</td>
<td>-0.5 [-0.6 to -0.1]</td>
<td>Continental to global</td>
<td>Med</td>
</tr>
<tr>
<td>Total Aerosol</td>
<td>-0.7 [-1.8 to -0.3]</td>
<td>Continental to global</td>
<td>Low</td>
</tr>
<tr>
<td>Linear contrails</td>
<td>0.61 [0.003 to 0.03]</td>
<td>Continental to global</td>
<td>Low</td>
</tr>
<tr>
<td><strong>Natural</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Solar insulance</td>
<td>0.12 [0.06 to 0.30]</td>
<td>Global</td>
<td>Low</td>
</tr>
<tr>
<td>Total net anthropogenic</td>
<td>1.6 [0.6 to 2.4]</td>
<td>Global</td>
<td></td>
</tr>
</tbody>
</table>

**Diagram:**
- **a)** Shows a bar graph with RF values for different RF terms.
- **b)** Shows a bell curve graph with RF values and a 90% confidence interval.

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Figure 5.4.6 Global annual emissions of anthropogenic GHGs from 1970 to 2004 (a). Share of different anthropogenic GHGs in total emissions in 2004 in terms of CO$_2$e (b). Share of different sectors in total anthropogenic GHG emissions in 2004 in terms of CO$_2$e (c). Forestry includes deforestation. Source: IPCC 2007. [Return to text]
Table 5.4.1 Atmospheric lifetimes and global warming potential (GWP) values for CO$_2$, CH$_4$, and N$_2$O. Sources: IPCC 2007; IPCC 2001.

<table>
<thead>
<tr>
<th>Greenhouse Gas</th>
<th>Radiative Efficiency</th>
<th>Atmospheric Lifetime</th>
<th>GWP 20 yr</th>
<th>GWP 100 yr</th>
<th>GWP 500 yr</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO$_2$</td>
<td>0.01548$^a$</td>
<td>~100 (5-200)$^b$</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>CH$_4$</td>
<td>0.00037</td>
<td>12</td>
<td>72</td>
<td>25</td>
<td>7.6</td>
</tr>
<tr>
<td>N$_2$O</td>
<td>0.0031</td>
<td>114</td>
<td>289</td>
<td>298</td>
<td>153</td>
</tr>
</tbody>
</table>

$^a$IPCC 2007 does not give a radiative efficiency for CO$_2$. IPCC 2001 lists the radiative efficiency of CO$_2$ as 0.01548 W/m$^2$/ppmv, but emphasizes this figure is to be used only for the computation of global warming potentials.

$^b$Precise estimation of the atmospheric lifetime of CO$_2$ is complicated by the multitude of removal mechanisms involved. Accepted values are around 100 years, with a wide error range.
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 is relative to other processes altered by reactive N. Source: Adapted from Pinder et al. 2012a.

<table>
<thead>
<tr>
<th>Process altered by reactive N</th>
<th>Radiative forcing effect</th>
<th>Relative size of effect</th>
<th>Description</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>N₂O</td>
<td>Warming</td>
<td>Large</td>
<td>Large</td>
<td>Parry et al. 2007; Smith et al. 2007</td>
</tr>
<tr>
<td>N deposition/fertilizer → CO₂ uptake by plants</td>
<td>Cooling</td>
<td>Large</td>
<td>Large</td>
<td>Sutton et al. 2008; Liu and Greaver 2009; Thomas et al. 2010</td>
</tr>
<tr>
<td>NOₓ → ground level O₃ → CO₂ uptake by plants</td>
<td>Warming</td>
<td>Large</td>
<td>Large</td>
<td>Felzer et al. 2004; Sitch et al. 2007; Pan et al. 2009;</td>
</tr>
<tr>
<td>Reaction</td>
<td>Type</td>
<td>Large Effect</td>
<td>Small Effect</td>
<td>Comment</td>
</tr>
<tr>
<td>----------</td>
<td>-------</td>
<td>--------------</td>
<td>--------------</td>
<td>---------</td>
</tr>
<tr>
<td>$\text{NO}_x \rightarrow \text{O}_3 \ &amp; \ \text{CH}_4$ in atmosphere</td>
<td>Cooling</td>
<td>Large</td>
<td>Small</td>
<td>NO$_x$ effects formation and destruction of O$_3$ and CH$_4$ in upper atmosphere</td>
</tr>
<tr>
<td>$\text{NO}_x \rightarrow \text{aerosols}$</td>
<td>Cooling</td>
<td>Medium</td>
<td>Small</td>
<td>Aerosols reflect and scatter solar radiation</td>
</tr>
<tr>
<td>$\text{NH}_3 \rightarrow \text{aerosols}$</td>
<td>Cooling</td>
<td>Small</td>
<td>Small</td>
<td>Aerosols reflect and scatter solar radiation</td>
</tr>
</tbody>
</table>

Arneth et al. 2010
Shindell et al. 2009
Shindell et al. 2009
### Table 5.4.3 California greenhouse gases and percent of annual total emitted in 1990, 2000 and 2009. Source: CARB 2010.

<table>
<thead>
<tr>
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</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MT CO₂e</td>
<td>Total</td>
<td>MT CO₂e</td>
<td>Total</td>
<td>MT CO₂e</td>
<td>Total</td>
</tr>
<tr>
<td>CO₂</td>
<td>390.0</td>
<td>90</td>
<td>408.9</td>
<td>88.1</td>
<td>393.2</td>
<td>86.1</td>
</tr>
<tr>
<td>CH₄</td>
<td>25.1</td>
<td>5.8</td>
<td>28.0</td>
<td>6.0</td>
<td>32.0</td>
<td>7.0</td>
</tr>
<tr>
<td>N₂O</td>
<td>16.5</td>
<td>3.8</td>
<td>16.0</td>
<td>3.5</td>
<td>15.2</td>
<td>3.3</td>
</tr>
<tr>
<td>SF₆</td>
<td>&lt;1.0</td>
<td>&lt;1.0</td>
<td>1.3</td>
<td>&lt;1.0</td>
<td>1.1</td>
<td>&lt;1.0</td>
</tr>
<tr>
<td>Other HFCs*</td>
<td>&lt;1.0</td>
<td>&lt;1.0</td>
<td>10</td>
<td>2.1</td>
<td>15.3</td>
<td>3.3</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>433.3</strong></td>
<td><strong>&lt;1.0</strong></td>
<td><strong>463.7</strong></td>
<td><strong>2.1</strong></td>
<td><strong>456.8</strong></td>
<td><strong>3.3</strong></td>
</tr>
</tbody>
</table>

*Other HFCs includes all other halogenated fluorocarbon gases
Table 5.4.4 Estimated emissions of N$_2$O, NO$_x$ and NH$_3$ by source and fate in California during 2005. Percent of each gas emitted by various sources are also provided. All N$_2$O emitted was assumed to remain in the atmosphere. NO$_x$ and NH$_3$, form secondary chemicals, aerosols and particulates and a certain fraction of the N in these constituents are deposited in California and the remaining are exported beyond state boundaries. As such, as export to the atmosphere or beyond the state boundary was calculated as the difference between total emissions and deposition. This table was developed using input and output data from the California N mass-balance developed in Chapter 4 of this report.

<table>
<thead>
<tr>
<th>Source and Fate of N Emissions</th>
<th>Statewide Emissions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Source of N Emissions</td>
<td>N$_2$O Gg N yr$^{-1}$</td>
</tr>
<tr>
<td>Fossil Fuel Combustion</td>
<td>9</td>
</tr>
<tr>
<td>Soil</td>
<td>24</td>
</tr>
<tr>
<td>Manure</td>
<td>2</td>
</tr>
<tr>
<td>Upwind sources</td>
<td>0</td>
</tr>
<tr>
<td>Wastewater</td>
<td>2</td>
</tr>
<tr>
<td>Fire</td>
<td>0</td>
</tr>
<tr>
<td>Surface Water &amp; Ground Water</td>
<td>2</td>
</tr>
</tbody>
</table>
### Fate of N Emissions

<table>
<thead>
<tr>
<th></th>
<th>38</th>
<th>100</th>
<th>406</th>
<th>100</th>
<th>268</th>
<th>100</th>
</tr>
</thead>
<tbody>
<tr>
<td>N deposition in California</td>
<td>0</td>
<td>0</td>
<td>135</td>
<td>33.3</td>
<td>67</td>
<td>25.0</td>
</tr>
<tr>
<td>Export to atmosphere or beyond California</td>
<td>38</td>
<td>100</td>
<td>270</td>
<td>66.7</td>
<td>201</td>
<td>75.0</td>
</tr>
</tbody>
</table>
Table 5.4.5 Default values and uncertainty range for IPCC emission factors used to calculate direct and indirect $N_2O$ emissions from agricultural soils in the California Greenhouse Gas Emissions Inventory. Sources: IPCC 2006; CARB 2009. [Return to text]

<table>
<thead>
<tr>
<th>Category</th>
<th>Emission Factor Description</th>
<th>Default Value</th>
<th>Uncertainty Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct $N_2O$</td>
<td>Proportion of N applied to soils via synthetic fertilizer, organic fertilizer, manure, N-fixing crops that is emitted as $N_2O$</td>
<td>0.01</td>
<td>0.003 - 0.03</td>
</tr>
<tr>
<td></td>
<td>Proportion of N deposited by livestock on pastures, rangeland, and paddocks that is emitted as $N_2O$</td>
<td>0.02</td>
<td>0.007 - 0.06</td>
</tr>
<tr>
<td></td>
<td>N emitted as $N_2O$ per unit area of cultivated organic soils (kg N per ha)</td>
<td>8</td>
<td>2-24</td>
</tr>
<tr>
<td>Indirect $N_2O$</td>
<td>Fraction of synthetic fertilizer N that volatilizes</td>
<td>0.1</td>
<td>0.03 - 0.3</td>
</tr>
<tr>
<td></td>
<td>Fraction of organic fertilizer and manure N that volatilizes</td>
<td>0.2</td>
<td>0.05 - 0.5</td>
</tr>
<tr>
<td></td>
<td>Leaching rate: Fraction of applied N lost to leaching and runoff</td>
<td>0.3</td>
<td>0.1 - 0.8</td>
</tr>
<tr>
<td></td>
<td>Proportion of N volatilized and re-deposited on soils that is emitted as $N_2O$</td>
<td>0.01</td>
<td>0.002 - 0.05</td>
</tr>
<tr>
<td></td>
<td>Proportion of N lost to leaching and runoff that is emitted as $N_2O$</td>
<td>0.0075</td>
<td>0.0005 -0.025</td>
</tr>
</tbody>
</table>

Chapter 5: Ecosystem services and human well-being
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