Global nitrogen deposition and carbon sinks

Land and ocean uptake of carbon dioxide plays a critical role in determining atmospheric carbon dioxide levels. Future increases in nitrogen deposition have been predicted to increase the size of these terrestrial and marine carbon sinks, but although higher rates of nitrogen deposition might enhance carbon uptake in northern and tropical forests, they will probably have less of an impact on ocean sink strength. Combined, the land and ocean sinks may sequester an additional 10% of anthropogenic cabon emissions by 2030 owing to increased nitrogen inputs, but a more conservative estimate of 1 to 2% is more likely. Thus nitrogen-induced increases in the strength of land and ocean sinks are unlikely to keep pace with future increases in carbon dioxide.

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At the beginning of the twenty-first century, human-induced climate change was well established as an issue of global significance. Despite greater political awareness and concern, the rate of growth of fossil-fuel carbon dioxide emissions increased from 1.3% per year in the 1990s to 3.3% per year between 2000 and 2006. Atmospheric concentrations of CO_2 rose at an average rate of 1.93 p.p.m. yr^{-1} over this period — faster than at any time since continuous monitoring began in 1959. This acceleration can be attributed largely to a rise in global economic activity, coupled to an increase in the carbon intensity of the global economy. But, on the basis of recent model studies, changes in the efficiency of the land and ocean sinks in removing anthropogenic CO_2 may also have contributed to the increase in atmospheric CO_2 growth rate over this period[1], albeit with a need for longer-term data to verify this component.

Together, the land and ocean sinks play a crucial role in determining the concentration of CO_2 in the Earth's atmosphere, sequestering the equivalent of up to half of the CO_2 emissions resulting from fossil-fuel use and cement production each year (Fig. 1). With an increase of more than 3% per year since 2000[2], these fossil-carbon-related emissions reached 7.2 ± 0.3 Pg of carbon per year in 2005. For the land and ocean carbon sinks to continue to sequester the same proportion of anthropogenic CO_2 emissions against this background of rising emissions would require an increase in their size — the so-called carbon dioxide fertilization effect — yet such an increase has not been observed[3].

In its Fourth Assessment Report (AR4), the Intergovernmental Panel on Climate Change (IPCC) noted that warming tends to reduce both land and ocean uptake of atmospheric CO_2, therefore increasing the fraction of anthropogenic emissions that stay in the atmosphere. Under the A2 storyline — an IPCC SRES scenario family based on a heterogeneous world of regionally focused economic growth, fragmented technological development and a continuously increasing population — this climate–carbon cycle feedback increases the projected warming at 2100 by more than 1 K. However, the coupled carbon–climate models used in AR4 do not include any effects of nutrient limitation or air pollution[3]. A very recent analysis of the response of terrestrial carbon fluxes to CO_2 fertilization and climate change showed that inclusion of the nitrogen cycle greatly reduces (by a factor of 3.8 by 2100) projected land carbon uptake in response to increasing atmospheric CO_2 concentration, while also reducing the sensitivity of the terrestrial carbon cycle to changes in temperature and precipitation[4].

The future of carbon sequestration by terrestrial and oceanic ecosystems therefore represents one of the greatest uncertainties in climate science[5,6], with an accurate description of the interaction between changing rates of reactive nitrogen (Nr) input and ecosystem carbon dynamics[7–12] being crucial to reducing this uncertainty.

PAST, PRESENT AND PROJECTED REACTIVE NITROGEN INPUTS

Forest regrowth, CO_2 fertilization, land use and climate change have all been suggested as key drivers of changes in late twentieth century carbon sink strengths. But throughout this period the land and oceans have also been experiencing rapidly changing inputs of Nr, with productivity and carbon dynamics in many terrestrial and marine ecosystems being partly determined by this Nr supply[11–14].

Alongside industrialization and rising emissions of nitrogen oxide (NO) from fossil-fuel burning, the intensification of agriculture and associated ammonia (NH_3) emissions has led to a three- to fivefold increase in Nr emissions over the last century[3] (Fig. 2). Global NO and NH_3 emissions are mainly terrestrial in origin and in 2000 stood at 52.1 and 64.6 Tg N yr^{-1} respectively[10]. In the atmosphere, NO may be converted to a number of other oxides of nitrogen (denoted collectively as NO_y), and NH_3 to NH_4 (denoted as NH_x), which are then deposited over the land

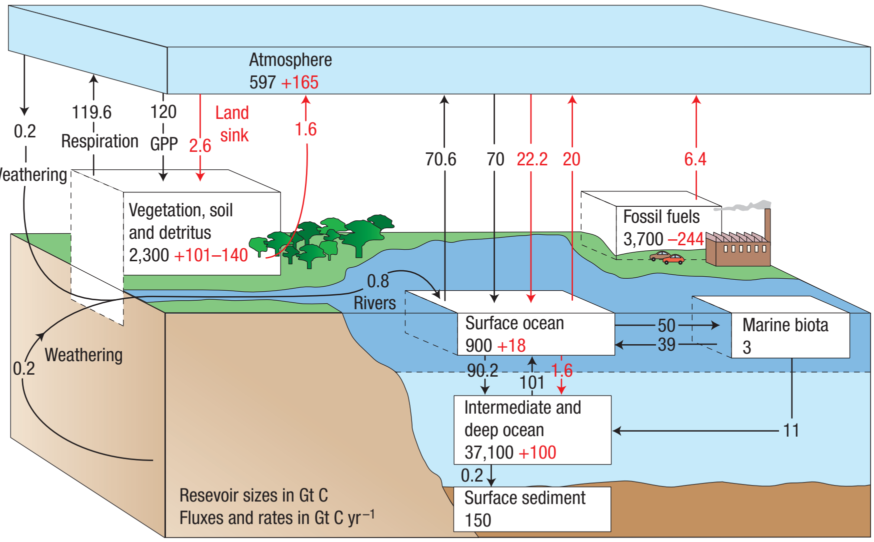

Figure 1 The global carbon cycle for the 1990s. This shows the main annual fluxes in units of Gt C yr^{-1}, with pre-industrial 'natural' fluxes in black and 'anthropogenic' fluxes in red. The net terrestrial loss is inferred from cumulative fossil fuel emissions minus atmospheric increase minus ocean storage. Gross fluxes generally have uncertainties greater than ±20%. Atmospheric carbon content and all cumulative fluxes since 1750 are as of the end of 1994. Reproduced from ref. 3. Copyright (2007) IPCC.

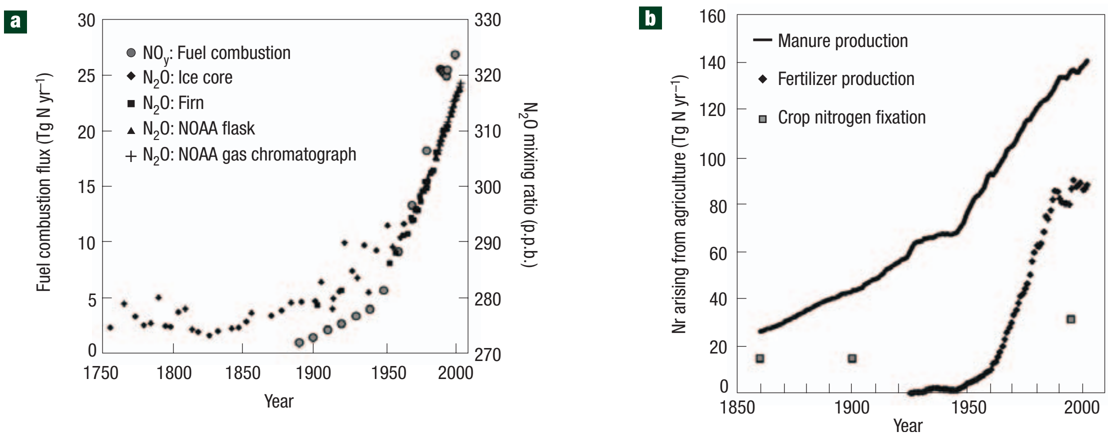

Figure 2 Global trends in reactive nitrogen production and emissions. **a**, Changes in the emissions of fuel combustion NO_y and atmospheric N_2O mixing ratios since 1750. Mixing ratios of N_2O provide the atmospheric measurement constraint on global changes in the nitrogen cycle. **b**, Changes in the indices of the global agricultural nitrogen cycle since 1850: the production of manure, fertilizer and estimates of crop nitrogen fixation. For data sources see http://www-eosdis.ornl.gov/ and http://www.cmdl.noaa.gov/. Reproduced from ref. 3. Copyright (2007) IPCC.

and oceans. Much of this is thought to be deposited on terrestrial ecosystems, with between 30 and 50% of NO_y and around 40% of NH_x deposited on the open ocean and on coastal zones[8,10].

Both NO and NH_3 emissions are predicted to increase still further in many regions during the twenty-first century (Fig. 3)[8,10,15]. Under the A2 emissions storyline, worldwide Nr deposition will increase by between 50 and 100% by 2030 relative to 2000, with the largest absolute increases occurring over East and South Asia. However, this scenario represents a rather pessimistic view of future Nr emissions for some regions. Existing legislation — such as that arising from the Gothenburg protocol — is likely to reduce emissions, at least in Europe. The Gothenburg protocol was adopted in 1999 to abate acidification, eutrophication and ground-level ozone. Full implementation of the protocol will cut Europe's NO emissions by 41% and its NH_3 emissions by 17% compared with 1990. However, despite such regional targets, the large growth in global population and demand for animal protein projected for 2030 is likely to mean that NH_3 emissions will become an increasingly important source of Nr deposition globally. Looking even further into the future using high-emissions scenarios, Nr deposition over land may increase by a factor of 2.5 by 2100[8], with a concurrent increase in deposition to marine systems of around 70%[16].

THE FOREST CARBON SINK

Much of the apparent increase in the terrestrial carbon sink observed in recent decades seems to have been associated with an

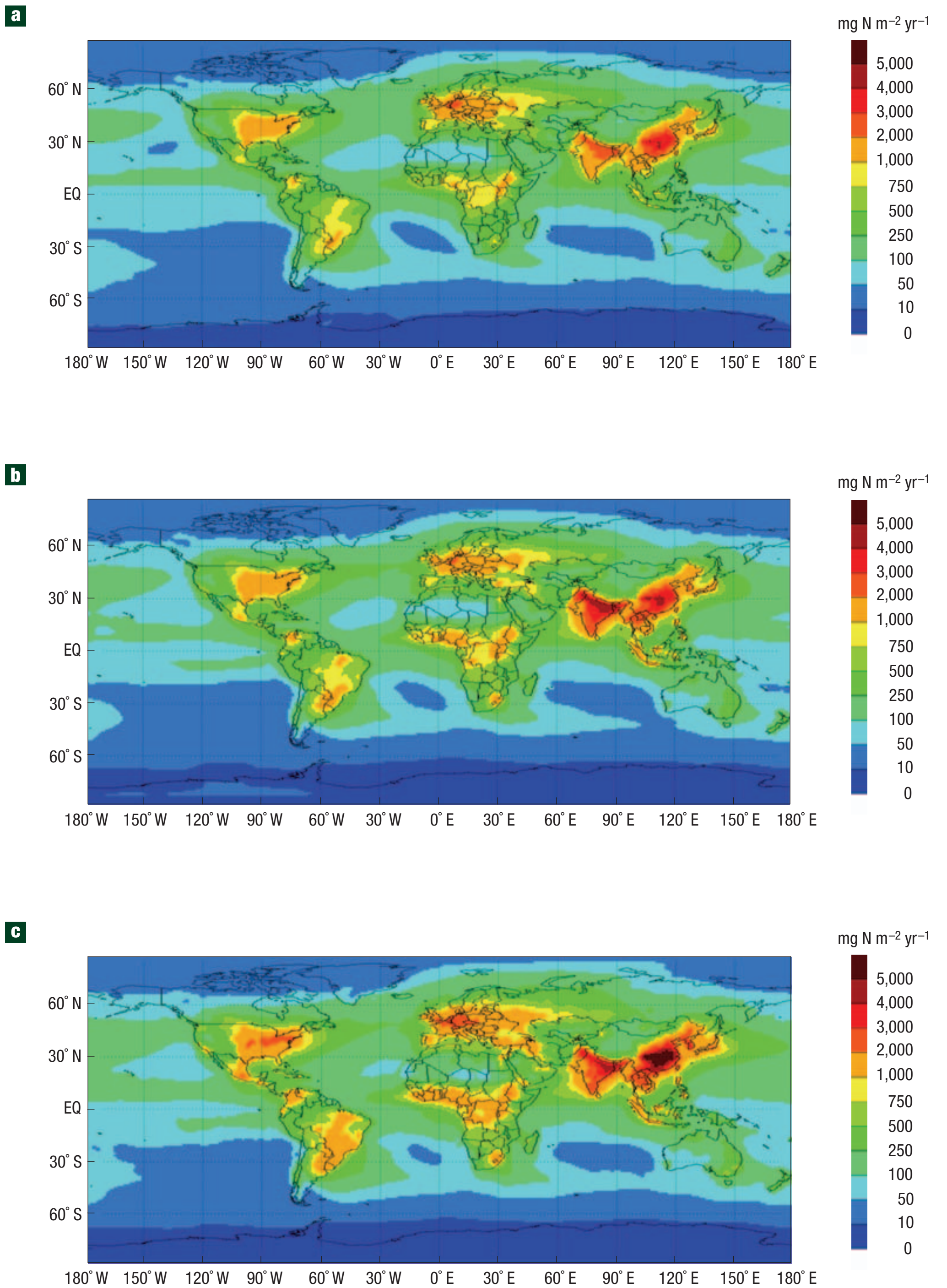

Figure 3 Global distribution of total Nr deposition with three different nitrogen deposition forcings. **a**, Year 2000 deposition field (denoted as S1). **b**, Year 2030 deposition field using a current emissions legislation scenario (denoted S2). **c**, Year 2030 deposition field using the SRES A2 emissions scenario (denoted S4). Adapted from ref. 10. Copyright (2006) American Geophysical Union.

observed worldwide increase in the growth of forests[17–20]. Quite small stimulations of the growth rate, death rate or decomposition rate in forest ecosystems can cause a large change in the carbon sink because the total carbon pool in these ecosystems is so substantial. The likelihood of Nr being implicated in any increased growth rate was stressed in earlier studies, when it became evident that many northern and temperate forests are nitrogen-limited, at least in terms of net carbon uptake[21,22], and that significant quantities of Nr in the form of nitrate and ammonium are deposited by wet and dry deposition (see Box 1) over industrialized and economically developed regions[23,24]. More recently, strong nitrogen limitation of net primary production, that is the net production of organic compounds from CO_2, in tropical forests has also been reported[25].

Box 1 Wet and dry reactive nitrogen deposition

Total nitrogen deposition includes both wet and dry deposition.

- Dry deposition refers to the deposition rate of nitrogen as a gas or aerosol (for example, NO2, HNO3, NH3) in a dry atmosphere, a process that depends on the surface and aerodynamic resistances. It is therefore dependent on how the gas species reacts with the surface itself (HNO3 is highly reactive and has a surface resistance of near-zero), the roughness of the surface and the wind speed. Dry deposition can thus be estimated if the atmospheric concentrations, the roughness and the wind speed are known. However, deposition of larger aerosols may also occur by sedimentation and impaction.
- Wet deposition involves the scavenging of pollutants by droplets of water, which are then deposited to the vegetation, soil or water surface as rain or mist. The ratio of wet to total deposition varies markedly over Europe, but is usually between 1:2 and 1:2.5.

The best information currently available on the influence of Nr deposition comes from temperate and boreal forests — experimental studies where nitrogen fertilizer is applied to the soil have produced a combined above- and below-ground sink enhancement of 36–48 gram of carbon for each gram of nitrogen applied[26,27]. However, reports of limited incorporation of labelled Nr inputs and high losses to drainage water in some forests have suggested that elevated Nr deposition has played only a minor role in boosting the size of the northern forest carbon sink[28]. Another estimate of the response to Nr deposition comes from data assembled from several forest studies encompassing a wide range of Nr deposition rates in Europe, Asia and North America. This shows an apparently linear and much stronger positive response of carbon uptake to the deposition rate of Nr, with as much as 200 grams of carbon being sequestered for every gram of total Nr deposited[29,30].

Reasons suggested for this wide disparity in the magnitude of response include the mode of Nr application[30] — when Nr is applied to forest soils artificially, a greater proportion may be intercepted by soil microbes or lost to drainage waters than in natural deposition when much of the Nr input may be taken up in the canopy[31]. On the basis of this ongoing debate, we hereafter define the upper limit of the response of carbon sequestration in northern forests to Nr input as 200 g C per g Nr, with an expected lower limit of 40 g C per g Nr.

For tropical forests, establishing even this kind of broad-range estimate for the magnitude of the response to Nr deposition is difficult. In a meta-analysis of data from 16 tropical forest studies, the overall response of aboveground net primary productivity to Nr input was dominated by eight sites on young (<1,000 yr old) Hawaiian soils[25]. These sites were believed to be prone to nitrogen limitation and indeed showed a marked positive response to Nr input. If these especially nitrogen-limited tropical forest sites were excluded, a positive response of aboveground net primary productivity to Nr input was obtained, which was similar in magnitude to that identified for temperate forests in the same meta-analysis. No significant response was seen in the only primary tropical forest site examined, but for secondary forests — defined as those resulting from human disturbance[32] — a response of carbon sequestration to Nr input of the same order as that reported for northern forests (40–200 g C per g Nr) appears possible.

With consistently high Nr deposition rates, deleterious effects may occur. Even where the vegetation is able to use the additional Nr effectively, chronic enrichment can result in reduced biodiversity in natural and semi-natural ecosystems[33]. Around 11% of natural vegetation currently receives in excess of 1 kg N ha^{-1} yr^{-1} as Nr deposition[10] and the terms 'nitrogen saturation' and 'critical load exceedance' have been used to describe the process whereby negative effects of high Nr deposition rates are observed and leakage of Nr from the ecosystem in the form of elevated gaseous and leaching losses is evident[34–36].

THE SOIL CARBON SINK

Evidence for changes in soil carbon sinks under Nr enrichment comes from a variety of sources, including changes in soil respiration/carbon mineralization rates in the laboratory or field, changes in litter decomposition rates, and changes in soil organic carbon stocks. Evidence is contradictory, with some studies suggesting that soil carbon may decrease under Nr enrichment, others suggesting no change, and others suggesting that soil carbon sinks may increase (see Supplementary Information, Table S1).

The response of the soil carbon sink to changing Nr deposition will depend on the balance between the Nr-induced increases in carbon inputs to the soil through increased plant growth, and the influence of increased Nr on carbon losses via soil organic carbon decomposition, respiration and mineralization. Higher C/N ratios tend to be associated with lower decomposition rates, so if C/N ratios decrease as Nr deposition increases, decomposition rates might be expected to increase. Nr deposition might also be expected to increase plant production in systems that are nitrogen-limited[29], although, as discussed previously, some authors have questioned the magnitude of this impact[28].

In agricultural soils, Nr fertilization can enhance soil organic carbon (SOC) mineralization[37,38] but studies of soil respiration suggest no change[39]. Mineralization has been shown to slow down at very high Nr concentrations[40], and in long-term experiments in which artificial Nr fertilizers were applied at much higher rates than natural deposition occurred, there were some small increases in SOC[41]. However, a recent examination of SOC at an experimental site receiving synthetic Nr fertilization over a 40–50 year period indicated a net decline in soil carbon[42].

In forest soils too, the evidence is contradictory. Increases in soil respiration (that is, short-term carbon loss) in response to Nr fertilization have been reported[43,44], whereas long-term (13 year) continuous high Nr addition suppressed soil respiration by 41% in both hardwood and pine stands[45]. It has also been suggested that (relatively) low rates of Nr addition can suppress soil respiration[29].

Additions of Nr to forest soils often appear to lower the C/N ratio without causing major changes in the total amount of soil carbon[46–48]. And an examination of soil carbon after 15 years of Nr addition to Harvard Forest found no significant change[49]. More recently, however, consistent increases in soil carbon in Nr-fertilized forest plots have been reported with accumulation rates appearing to be strongly dependent on the soil's nitrogen status[27]. Nr fertilization also increased SOC sequestration at nitrogen-rich sites, where the tree-growth response was low, suggesting that reduced decomposition rates after Nr addition may contribute to soil carbon accumulation[27].

The contradictory evidence suggests that it may not be possible to make sweeping statements about how soil carbon sinks will

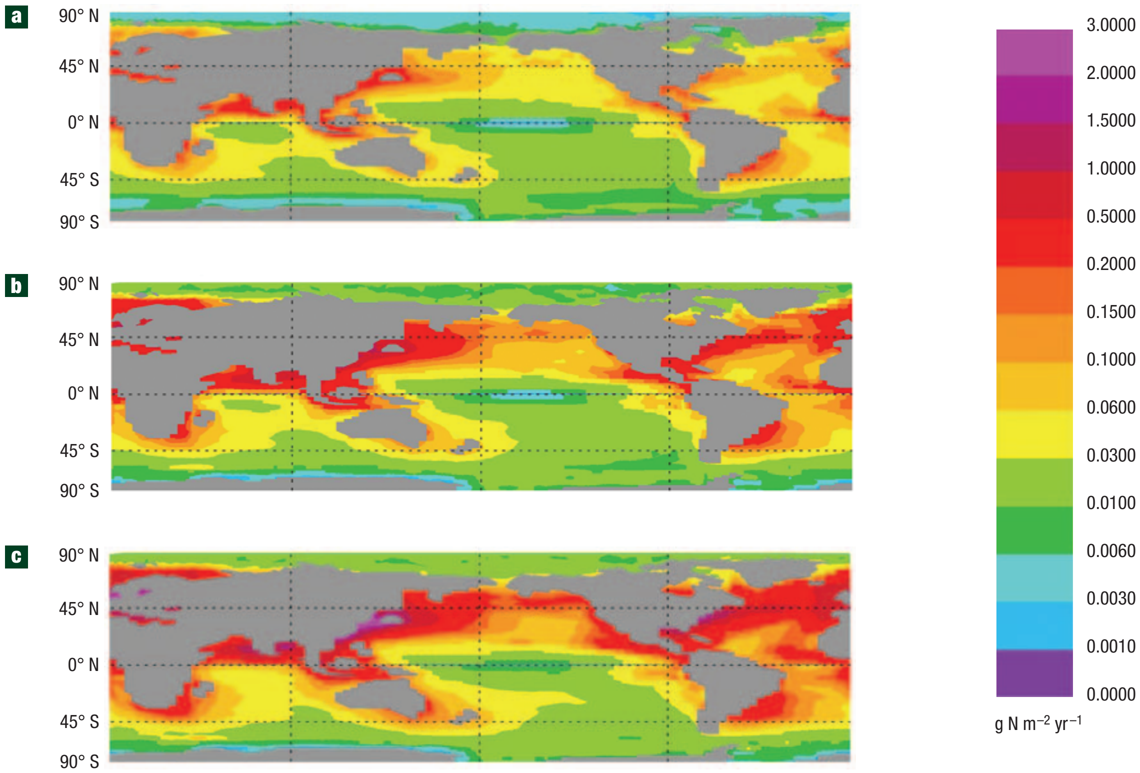

Figure 4 Global distribution of oceanic nitrogen deposition with three different nitrogen deposition forcings. **a**, Pre-industrial distribution, comprising a total net input of 22.14 Tg N yr^{-1} and excluding human-induced NO and NH_3 emissions. **b**, 1990s distribution, comprising a total net input of 38.9 Tg N yr^{-1}. **c**, IPCC-A1FI distribution, comprising a total net input of 68.9 Tg N yr−1 and using the same spatial distribution of emissions as that used for the 1990s. All distributions are from the final year (year 64) of simulations and exclude oceanic NH_3 emissions. Units of deposition are g inorganic N m^{-2} yr^{-1}. Reproduced from ref. 16. Copyright (2007) American Geophysical Union.

respond to increased Nr deposition. Laboratory incubations of soils from two long-term forest fertilization experiments showed a 30% reduction of the mineralization rate in the mor layer of plots that had received Nr additions, compared with control plots[50], and modelling of bomb-^{14}C data from one of these sites, showed that the reduced mineralization rate would significantly increase SOC stocks in the long term[51]. About 60% of this increase was estimated to be due to a decreased decomposition rate, and the rest due to increased litter production. It has been suggested that the decreased decomposition rate was driven by a fertilizer-induced increase in decomposer efficiency (production-to-assimilation ratio), a more rapid rate of decrease in litter quality, and a decrease in decomposer basic growth rate[50]. Overall then, elevated Nr deposition may lead to a decrease in the mineralization rate and an accumulation of carbon in the mor layer[52]. Moreover, very recently in northern temperate forests, increased SOC accumulation in surface soil layers under low mineral nitrogen addition rates has been reported. This has been attributed to decreased SOC decomposition rates rather than increased detrital inputs[53].

It is not clear whether large increases in soil carbon could be expected in areas that receive excess atmospheric Nr deposition[46]. The evidence remains mixed (Supplementary Information, Table S1), but the majority of recent studies do suggest that Nr enrichment may suppress soil carbon loss[26,27,29,30–54] and may therefore serve to enhance soil carbon sinks. SOC responses to Nr in the studies presented in Table S1 range from 0 g C per g Nr (refs 46,47,49) to 23 g C per g Nr (ref. 53), with some studies for forest soils showing an increase in SOC ranging from 7–23 g C per g Nr (refs 26–28,53). As such, soil carbon stocks may increase as a consequence of increased Nr deposition in the future, but the saturation of this response remains unexplored.

THE OCEANIC CARBON SINK

The long-term ocean sinks for CO_2 are thought to range from about 1.5–2.2 Pg C yr^{-1}, which corresponds to approximately 25% of fossil-carbon emissions[62–69]. On the basis of observations over the past 50 years, the Atlantic Ocean takes up about 41% of the annual global ocean flux of 1.5 ± 0.25 Pg C yr^{-1}, whereas the Pacific takes up only 33% of the global flux owing to the compensating impacts of the large CO_2 source in the equatorial Pacific[69–71]. The remaining 25% is taken up by the Indian and Southern oceans.

Recent evidence for increased growth of CO_2 concentrations in the atmosphere since 2000 have raised concerns about the efficiency of the ocean carbon sink[1,72–74]. The surface ocean today appears to be less efficient at taking up CO_2 from the atmosphere than the pre-industrial ocean, resulting in a positive climate feedback. Recent modelling and field observation efforts have also suggested substantial reductions in the CO_2 sink strengths in some specific oceanic areas over the last 10–15 years[1,72–75], and a small increase in the CO_2 flux in the equatorial Pacific during the past 9 years[71]. A reported reduction in CO_2 uptake in the Southern Ocean has been attributed to human-induced alterations in wind speeds[74].

The potential magnitude of such climate–carbon feedbacks has been examined in several modelling studies[76–81]. It is estimated that, owing to the warming of the surface ocean, approximately 9–14% of the CO_2 that would have been stored in the ocean will be retained in the atmosphere by 2100[80]. Similar results were obtained using the NCAR Climate System Model[81,82].

As with terrestrial ecosystems, changing Nr input has the potential to alter the productivity and carbon dynamics of marine ecosystems, with possible consequences in terms of net CO_2 sequestration and species abundances[16,83]. A very recent analysis has suggested that anthropogenic atmospheric Nr deposition to the open ocean may currently support ~0.3 Pg C yr^{-1} of primary production relative to that in 1860[84]. Using model simulations based on the response to three different atmospheric inorganic nitrogen deposition scenarios to 2100, a widespread increase in Nr deposition to the oceans has been predicted[16] (Fig. 4), but with only modest impacts on export production (the amount of sinking particulate organic carbon) and air–sea CO_2 exchange. The projected changes in Nr deposition at 2100 using the IPCC's fossil-fuel intensive A1FI SRES scenario — which assumes a future world of very rapid economic growth, rapid introduction of new and more efficient technologies and a mid-century peak in global population — resulted in increased primary production (0.98 Pg C yr^{-1}) and export production (0.16 Pg C yr^{-1}), and a decrease in atmospheric pCO_2 of 1.66 p.p.m. relative to the pre-industrial control. However, this rather limited response to changes in atmospheric deposition ignores the additional Nr inputs to coastal regions via river discharge.

Riverine Nr fluxes have almost doubled since the pre-industrial era and most Nr is delivered to coastal waters, with current export by this route totalling ~60 Tg N yr^{-1} (ref. 15). The amount of Nr thus transported is predicted to increase further to ~75 Tg N yr^{-1} by 2050. The potential impact of such elevated Nr inputs on net oceanic carbon sequestration could be expected to be similar to that predicted for increased inputs from the atmosphere, as the levels of additional Nr are of a similar magnitude. However, riverine Nr inputs may be concentrated in increasingly nitrogen-replete coastal areas around the world, which may limit this response and, where large increases in primary production are induced, may result in the expansion of anoxic zones[15].

Recent coupled climate models also indicate that, with increased stratification of the oceans over the next century, there will be a corresponding reduction in Nr inputs from subsurface waters and so a modest decrease in primary production[81,85]. These changes may have a considerable impact on phytoplankton community structure, leading to increased dominance by coccolithophorids, dinoflagellates and nitrogen-fixing diazotrophs, and to decreased abundances of diatoms[86,87].

Although there are considerable differences in the relative magnitudes of the individual potential ocean feedback processes, most models project a net decrease in the fraction of anthropogenic CO_2 sequestered by the ocean over time[80]. Recent models have estimated oceanic uptake of anthropogenic CO_2 by 2100 ranging from about 4–8 Pg C yr^{-1}, depending on the CO_2 emission scenario used in the model[88]. This estimate is about a factor of 2–4 times higher than the present day value of 2.2 ± 0.5 Pg C yr^{-1} but still lags behind the projected rate of increase of anthropogenic CO_2 emissions. With the response of oceanic carbon uptake to elevated Nr deposition unlikely to much exceed an additional 0.16 Pg C yr^{-1} by 2100 relative to the pre-industrial state, and increased Nr inputs from rivers achieving, at most, a similar response, it would seem that the role of changing Nr availability in determining the strength of the oceanic carbon sink during the twenty-first century will be dwarfed by those of climate and atmospheric CO_2 concentration.

FUTURE IMPACT OF CHANGING NR INPUTS

Despite greater controls on emissions in some countries, there seems little doubt that many terrestrial and marine ecosystems will receive an increasing supply of Nr over the next few decades. What then are the likely consequences for carbon sink strengths? Will an increasingly heavy dose of Nr serve to significantly reduce the growth rate of atmospheric CO_2 concentrations?

In the oceans the projected enhancement of net CO_2 sequestration as a result of elevated Nr deposition rates and riverine inputs appears rather limited. Even assuming the response to Nr inputs from rivers mimics that predicted for the more diffuse atmospheric inputs, a response of around 0.3 Pg C yr^{-1} relative to the pre-industrial state appears to be at the upper limit of what can be expected in the latter half of the twenty-first century.

For the soil carbon sink a response in SOC ranging from 0–23 g C per g Nr encompasses much of the reported variation, with those studies that report a positive response in SOC (7–23 g C per g Nr) being for forest soils. For non-forest areas, we have assumed zero net response of carbon sequestration to elevated Nr input, and we regard the total forest response of 40–200 g C per g Nr as a range that encompasses the SOC component. Certainly, a similar SOC response may emerge for non-forest soils and a great deal more research is required to establish the mechanism by which Nr input may reduce soil carbon loss and at what level of input such a response might become saturated. As most agricultural land already receives substantial Nr inputs as fertilizer, additional Nr deposition would not be expected to have a large effect on carbon sequestration in these soils. The large soil carbon stocks in uncultivated boreal and tropical peatlands may respond more strongly to increased reactive Nr inputs, but there are currently insufficient data to properly assess this response.

Likewise, the positive response to elevated Nr inputs reported recently for primary producers in some freshwater ecosystems[14] requires further investigation, with the implications for future carbon sequestration in mires, lakes and reservoirs around the world being significant.

Currently, it is in forests that there would appear to be the greatest potential for rising emissions of anthropogenic Nr to help mitigate against those of anthropogenic CO_2. Total Nr deposition over much of Europe and North America already exceeds 4 kg N ha^{-1} yr^{-1} and, using the IPCC's A2 emissions scenario to 2030, an additional deposition rate of ~2 kg N ha^{-1} yr^{-1} is towards the upper limit[10] of what can be expected for the 1.68 billion ha of forests on these continents[89] (Fig. 4). If one assumes a ratio of net carbon sequestration to Nr deposition of 200:1[29,30] and that key factors such as forest area, distribution, management and age class structure[90] remain relatively constant, then one might see an additional 0.67 Pg C uptake by these forests each year by 2030.

Though suffering from a paucity of data compared with northern forests, projected changes in the rates and distribution of Nr deposition also have the potential to induce a large response in secondary tropical forests. Current deposition rates to these areas are generally <1 kg Nr ha^{-1} yr^{-1}, but under the A2 scenario many will see rates double by 2030, with an additional 1 kg Nr ha^{-1} yr^{-1} possible. Using the same assumptions about area, distribution, management and age class structure as used for the northern forests, the response of the ~0.7 billion ha of secondary forest in the tropics to such elevated Nr inputs has the potential to induce an additional 0.14 Pg C uptake each year by 2030 (see Supplementary Information for details).

Large increases in Nr deposition to both northern and tropical forests over the next few decades could therefore help to sequester around 10% — some 3 billion tonnes — of annual anthropogenic CO_2 emissions. The caveats to such extrapolations are, of course, legion, and we consider this estimate to be an upper limit.

Using more conservative estimates of carbon sequestration by forests in response to Nr deposition would bring this figure down to a still considerable 1–2%. Equally importantly, the A2 emissions scenario itself is likely to overestimate Nr deposition rates for many northern forests. Incorporating existing legislation on air pollutant emissions controls into projections produces a 5–20% reduction in Nr deposition over most of Europe and an increase of only 5–20% over North America for 2030, relative to 2000[10]. For most tropical forests, a substantial increase in Nr deposition is predicted even when existing air pollution legislation is included in projections, with a 40–100% increase in NH_x deposition rates across Central and South America, Africa and part of Asia[10]. It is in these regions then, that forest carbon sequestration may be most affected, yet until robust quantitative figures on this response are available, we can only speculate as to its global significance.

Overall, our analysis of measurements and model studies indicates that the likelihood of greatly enhanced global CO_2 sequestration resulting from future changes in Nr deposition is low. Even if Nr emissions were to follow the more pessimistic emissions scenarios and large increases in the strengths of the terrestrial and oceanic carbon sinks were achieved, this may be offset by any simultaneous enhancement of N_2O emissions[84]. A doubling of the year 2000 Nr emissions by 2030 may go some way to achieving the 3 billion tonnes of additional CO_2 sequestration in northern and tropical forests each year, but it would also induce global annual emissions of between 0.54 and 2.7 billion tonnes (emission factor of 1% (ref. 91) and 5% (ref. 92) respectively, see Supplementary Information for details) of CO_2 equivalent, in the form of NO_2, via increased nitrification and denitrification on land and in the oceans. Such pollution-swapping would greatly off-set the net climate change mitigation benefits.

The vast carbon sinks that are the world's oceans, forests and soils currently play a crucial role in buffering accelerating anthropogenic CO_2 emissions. Whether the strength of these sinks can be maintained in the face of land use and climate change during the twenty-first century remains a key uncertainty in model predictions. Though there is some potential for enhancing such carbon sinks through elevated Nr inputs, it is the protection of the existing terrestrial carbon sink from deforestation and land-use change that is likely to provide the greater climate change mitigation benefits in coming decades.

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D.S.R. drafted the manuscript and developed the estimates of the potential global carbon sink response to future Nr inputs. P.S., J.G., F.D and R.A.F. each drafted sections of the manuscript. All authors contributed to further development and discussion of the manuscript.

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