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REVIEW ARTICLE

Forests and their importance in the global carbon and nitrogen balance – a review with reflections

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Abstract

Carbon (C) and reactive nitrogen (Nr) are two elements increasing in the Biosphere due to human activity. CO_2 in atmosphere is increasing due to deforestation for at least 150 years, and burning of fossil fuels since about 100 years at an increasing speed. C is a dominating element in Biosphere, and the biggest stores of C appear in forest biomass and forest soils. The forest growth per hectare has increased, due to increases of CO_2, temperature and Nr-deposition, but total global C-sequestration in forests has nevertheless decreased due to deforestation and burning, and in spite many new plantations.

Nr is the limiting element for growth in most forests, but is found in much lower amounts as C, usually in specific C/N-relations. Estimates suggest on an average 40 times less Nr in forest ecosystems compared to C. The Nr fluxes and accumulation has increased relatively much more than the C-fluxes, which significantly supported the C-sequestration in forests. In future both CO_2 increase (associated with temperature increase), and N-deposition are suggested to increase even more, and this might have detrimental effects on tree species and the whole forest ecosystem, especially in the temperate zones.

Key words

global carbon, nitrogen, forests, deposition

Shortages

t = tonne = 10^6g
Mt = Megatonne = Tg = Teragram = 10^{12}g
Gt = Gigatonne = 10^{15}g = Pg = Picagram

Introduction

Forests on the Earth today are to a great extent impacted by humans. About 36% of our forests are considered as more or less virgin forests, while the majority are more or less managed, some planted, often ditched and sometimes fertilized forests. Still many tropical forests are thinned or cut for other purposes, and about 13 mil-

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lion ha per year are deforested, while about 8 million ha are new plantations. Thus, most countries show more deforestation than plantation, and Africa, Australia and South America have the highest deforestation figures. In Europe including Russia, and Asia there is a slight positive trend in forested areas. In total the forest area is around 4000 million ha 2010 (FAO 2010).

The estimated land cover of forests is almost 31% on the Earth, i.e. in the same range as grass- and bush land areas or infertile areas. The agricultural land areas are in the range of 10%, but they are dominant concerning effects on the N-cycle.

New forests build up huge amounts of biomass, consisting mainly of carbon (C), oxygen (O), hydrogen (H) and nitrogen (N) and a few percentage of minerals like P, K, Ca and Mg and microelements like B, Cu, Fe, Mo and Zn. Carbon is bound as organic matter in the biomass, but it is also found in even higher amounts in soils as ”organic matter” in different decomposition stages. A net accumulation of C does not, or only to a small extent, appears in old and mature forests, as there is a balance between accumulation and decomposing processes. In new forests, however, the trees are building up new biomass and more C is accumulated also in the soils.

N is bound in the biomass always in specific relation to C in different plant material, and N is the most important element limiting growth in forests. Principally it is impossible to discuss the C-behaviour, its uptake and decomposition, without simultaneously considering the N-assimilation in plants, its decomposition and recirculation and eventual return to the atmosphere (Aber et al. 1991, 2003). This is of special importance as the N-cycle so far has been affected by humans to a much higher degree than the C-cycle, due to industrial N-fixation (Falkowski et al. 2000; Canfield et al. 2010). The fixed N is spread as fertilizers, but later evaporated as ammonia from soils, manure and wastewater into the atmosphere, and later deposited to a high degree in forests. Almost similar amounts, but of oxidized N come to the atmosphere at combustion reactions between N_2 and O_2. Thus, human effects on CO_2 levels in the atmosphere are of vital interest for forests, as well as the emissions of nitrogen in the form of nitrogen oxides or ammonia into the atmosphere. And it is no doubt that existing forest stands are stressed by all these factors in a changing environment (Nihlgård 1985, 1997). Also, we have to recognize activities such as deforestation, livestock grazing etc., that may have impact on the global forests as important as the effects of increasing CO_2 concentration per se (Amthor 1995).

The aim of this review is to summarize results indicating the impact on forests due to combined effects of increasing CO_2 levels, and emitted nitrogen into the atmosphere, finally reaching the forests.

The carbon cycle

Carbon stores

In forests the total amount of C is estimated to 1080 Gt, corresponding to about 45% of the total C content in global ecosystems. Most of this is soil carbon, 790 Gt (Dixon et al. 1994), and 289 Gt are in the biomass (FAO 2010). C is fixed in vegetation through photosynthesis, taken as CO_2 from the atmosphere. The CO_2-concentration in the atmosphere has continuously risen since humans started cutting down forests, and especially since we started burning coal and oil. It is now on a level that causes huge problems, as infrared radiation is prevented leaving our atmosphere, so we have got also a rising temperature (Alley et al. 2007).

Estimates of the amounts released into atmosphere from 1850 to 2000 ends up with >300 Gt due to burning of fossil fuels, and >190 Gt due to deforestation. These emitted amounts have either accumulated in the atmosphere (≈190 Gt), or in about equal amounts been bound in seawater (150 Gt) and assimilated by vegetation, mainly bound in forests (150 Gt). Increased CO_2 and temperature will physiologically result in increased tree growth (e.g. Suan-Chin Wong 1990; Cole et al. 2010), but there are also naturally counteracting effects, e.g. from forest fires (Goodale 2002). The amounts of C in different continents since 1990 show that Europe and North America have accumulated more in forests, while decreasing amounts are found in Asia (in spite large forest plantations in China), in South America, Africa and Oceania (FAO 2010).

Carbon fluxes

The yearly fluxes of C are today estimated to be about 7,2 Gt C/yr from fossil fuel burning and cement production, and about 1,6 Gt C/yr due to deforestation. In the atmosphere the increase is today about 4,1 Gt C/yr, the sea absorbs about 2,2 Gt C/yr and forests about 2,6 Gt C/yr. The net C flux to land vegetation, mainly forests, thus ends up with an absorption of about 0,9 Gt C/yr, or 900 Mt/yr (Falkowski et al. 2000; Solomon et al. 2007). In the sea there is also a sedimentation process, principally by carbonate fallout in corals and as $CaCO_3$ in deep sediments, but this is a small amount compared to the steady increase of bicarbonate and carbonic acid, causing a slightly decreased pH of the sea water.

In forests the increased CO_2 level has increased the growth of trees and most other vegetation. Estimates roughly indicate that forest trees in Europe in general grow almost 50% quicker today than 50 years ago. This is of course not only depending on the CO_2 increase, but perhaps even more on the increase in temperature and in the nitrogen deposition (Churkina et al. 2008; Jain et al. 2009). In many regions, and especially in South America and the Oceania, the plantations are to 80–90% of introduced, foreign tree species (FAO 2010). This may be positive for the C-sequestration, but negative especially for biodiversity.

To sum up the emissions of CO_2 are balanced to about 43% by uptake in forests and in the sea, while about 57% remains and accumulate in the atmosphere. The CO_2-increase and increased temperature has theoretically contributed to an increase in forest growth per hectare and year. More C in forests and soils automatically means increased amounts also of N and vice versa.

The nitrogen cycle

Nitrogen shows a very complex biogeochemical cycle on the Earth. The appearance of 78% in the Atmosphere has no parallelism to the very low amounts in the Biosphere, where much less than one percentage of nitrogen on the Earth exist. It is called *reactive nitrogen (Nr)*, as a contrast to the stabile N_2-gas (Galloway and Cowling 2002). Nr is taken up by plants mainly as ammonium or nitrate, and is used as amino acids in proteins. In spite the small amounts in Biosphere Nr is the most limiting element for growth of trees and most other plants.

Most N on the Earth is in the Lithosphere, though the amounts estimated are very varying, second in the Atmosphere, third in the Hydrosphere and fourth is the tiny amount in the Biosphere. All the possible ways for Nr to come into and disappear from the Biosphere are described up to our knowledge very well in different papers (Aber et al. 2003; Bouwman et al. 1997, 2009; Canfield 2010; Galloway et al. 2003, 2004, 2008; Vitousek et al. 1997, 2003). The below comments are illustrating some of the problems and difficulties in estimation of Nr.

Stores of Nr in the biosphere

The amounts of N in the Biosphere are estimated to about 20 Gt in vegetation, mostly on land and forests, and to about 130 Gt in soil organic matter (SOM). This corresponds to average C/N-ratios of 32 and 12 respectively, but such C/N-figures are lower than reported from forests, e.g. Australian forests (Snowdon et al. 2005). Higher C/N-ratios should be used for forest ecosystems, and 40–50 are often used.

Since 1950 we have increasingly fertilized our agricultural soils with Nr, today corresponding to at least 148 Mt/yr (FAO 2010, Canfield et al. 2010). The greatest increase in use of Nr is from Asia, while North America and Europe have stabilized their fertilizer amounts. Manure from cattle, pigs etc. to a large extent embrace this fertilizing Nr, and is thus included in the 148 Mt/yr (Tab. 1). Human crops of N-fixing plants contribute with another 43–46 Mt/yr. Natural N-fixation is around 110 Mt/yr. All uses of N ends up in an increase of the net N-emission into the atmosphere.

Nr-emissions to atmosphere

Ammonia (NH_3) evaporates from urine, animal manure and wastewater, but also from calcareous soils and many human sources, and it´s difficult to avoid these emissions to the atmosphere (Becker and Graves 2004). NH_3 is quickly turned into ammonium ions (NH_4^+), which are widely distributed as small particles and deposited both as wet and dry deposition. Bouwman et al. (1997, 2009) estimated the global NH_3 emissions to be about 54 Mt/yr, some of it from burning biomass. In Europe the emissions are reported to decrease from 5 Mt/yr during 1990 to about 4 Mt/yr 2010, almost following the regulations according to legislation (EEA 2010). Here I suggest an approximated global value of 40 Mt/yr. However, concerning the NH_3 emissions these may be underestimated, as from satellite observations Clarisse et al. (2009) could register areas with NH_3 concentrations in the atmosphere much higher than expected from other measurements.

Tab. 1. Reactive nitrogen (Nr) fluxes on land areas of the Earth. The values are collected from different sources, but basically from Vitousek et al. 1997; Galloway et al. 2008; Bouwman et al. 2009; Canfield 2010 and FAO 2008 and 2010

Nr on terrestrial areas 2010	To vegetation, soil, water Mt/yr	To atmosphere Mt/yr
Fertilization	148	
N-fixing crops	43	
Burning biomass ($NO_x + NH_3$)		30
Draining wetlands	10	
Deforestation	13	7
NOx-emissions (vechicles)		25
Lightning fixing N (NOx)		3
Other NH_3-emissions	–40	40
Natural N-fixation	110	
Terrestrial denitrification (N_2, N_2O)	–100	
Losses to sea	–69	
Total Nr to atmosphere ≈		105
Total Nr in deposition ≈		105
Yearly terrestrial Nr accumulation	115	≈ 70

Burning wood fuel emit Nr to the Atmosphere both as ammonia and as nitrogen oxides of about 30 Mt/yr. From vehicles and oil and coal heating plants we emit increasing amounts of nitrogen oxides, in spite regulations with catalysers, as the number of cars steadily increases, and NOx emissions are estimated to be at least 25 Mt/yr (Canfield 2010). Lightning in nature contributes to terrestrial areas with another ≈3 Mt/yr of nitrogen oxides.

In nature, however, a lot of nitrogen is denitrified and might reach the atmosphere as neutral N_2-gas or eventually, to a much smaller percentage, as N_2O, a green house gas also affecting the ozone layer, and reaching far up in the atmosphere. The total denitrification process is estimated by Canfield (2010) to be in the range of about 100 Mt/yr from terrestrial areas. Another loss is leaching of nitrate and ammonium that will reach the sea. Adding up what is immediately accumulated in the terrestrial environment one get ≈ 115 Mt N/yr (Tab. 1.). To this will be added nitrogen emitted or formed directly into the atmosphere, which by the time will also reach the ground (Tab. 1).

Deposition of N and its effects in forests

Summarizing (Tab.) the different figures for emission to air, expected to be deposited to the ground and then especially to forests, the net figure will be around 105 Mt/yr (Galloway et al. 2008). Galloway et al. (2008) tried to illustrate the global deposition of NOx and NHy, and it´s quite clear that the highest amounts hit the terrestrial ecosystems, but it is a rough estimate that of the deposited 105 Mt/yr about 70 Mt will hit terrestrial ecosystems. The amount specifically deposited to forests are of course even more difficult to estimate, and 20 Mt/yr is probably an underestimate, it could as well be 30–40 Mt/yr. 20 Mt/yr corresponds to an average deposition of N in forested areas of 5 kg/yr. We know that in industrialized and agricultural areas the dry and wet deposition may reach 30–60 kg N/ha.yr, while in northernmost parts of the temperate forests the amounts are in the range 1–2 kg/ha.yr. We also know that in most areas the deposited Nr is accumulated and causes increased growth.

In Sweden, for example, we have monitored forests since 1923, and we know approximately how much the growth per hectare has increased since then (Skogsstatistisk Årsbok 1942–2010). Today the productivity is about 80–120% higher. The strongest increase can be observed since around 1970, with about 50%. This is of course due to several factors; forestry have introduced more productive provenances and made many efficient plantations, sometimes of new species. The nitrogen deposition has increased especially since 1960s, and the continuous CO_2-increase has been followed by a temperature increase. We know that they all contribute to increased growth, even though sometimes water and mineral nutrient limitations may counteract (Diaz et al. 1993). Increased forest growth is, however, reported from many areas in Europe, even from forests not managed very efficient. This is why Nr-deposition and CO_2-effects are the most likely explanations.

Several other variables in forests are affected by an increased N and C accumulation; the decomposer diversity is changing, and the flora is showing more and more nitrogen loving species of e.g. the genus Chamaenerion, Circaea, Circium. Rubus, Urtica. The access to balancing minerals (K, Ca, Mg, P, and esp. micronutrients like B, Cu) is lowered and the soils should be more easily acidified. As nitrogen usually is limiting for growth, and now is added as the only nutrient, one should expect imbalances to nitrogen to appear by the time. Even if the weathering rate is slightly increased due to temperature increase, it is not enough according to models if nitrogen addition continues.

Nitrogen imbalances will favour different parasites on trees, especially parasitic fungi. Phytophthora species are well known to increase in soils with excess of nitrogen, and Armillaria species are linked to these attacks. To my knowledge no-one has studied e.g. ash and elm dieback and the dependence of these fungi outbreaks on imbalanced nutritional conditions (and thus the relation to N-emissions). In Finland, however, it is proven that B is an obvious deficient micronutrient, and this is well known to appear at nitrogen fertilization of forest stands. Boron is important for plants in the defence against parasitic fungi.

Carbon/nitrogen balances

In the soil N is decomposed and used by decomposing organisms, and it is released to atmosphere at a slower rate than C, why it accumulate relative to C, and lower the C/N-ratios from 40–100 down to 20–30 or even to values down to ≈10. Empiric measurements indicate that when the C/N-ratio goes below 20 in soil, the risk for nitrate leakage to ground water and runoff water increases.

Based on C/N-ratios one can roughly estimate the amounts of nitrogen bound in the forests due to the increased amounts of C (Schindler and Bayley 1993). The C/N-ratios varies from 20–30 in photosynthesising leaves, to 120–180 in woody material like branches and stems. The C/N-ratio in forest biomass on an average can vary from 50 to 100, and in forest soils 15–35 (cf Callesen et al. 2007; Galloway 2008). As an average here I use C/N = 40 for the whole forest ecosystem, including both biomass and soil.

Using a C/N-ratio of 40 and an estimate of Nr-deposited to forests of 20Mt/yr, the corresponding amount of C accumulated in forests will be 800 Mt/yr or 0,8 Gt/yr. This is a C-sequestration explaining why CO_2 has not increased as much as it should according to earlier models. In addition, the deposition of high amounts of N to forests causes increased growth and increased biological soil acidification. For example a deposition of 10 kg N/yr will ask for an increased uptake of K (4 kg), Ca (4–10 kg) and Mg (1 kg). These nutrients as well as specific micronutrients like B, Cu, Mo and Zn may easily become deficient in many soil types (Rennenberg et al. 2009).

The future; Conclusions and recommendations

The IPCC report (2007) is very clear about the future carbon dioxide problems if we do not manage to decrease emissions from fossil fuels and deforestation. The prognosis for forests must be taken seriously, concerning both the direct impact of CO_2 and associated increased temperature.

Concerning N we can conclude that N is an important driving variable behind the increased forest growth, especially noted in temperate forests. N deposition is also important in understanding a continuous soil acidification, due to biological processes and a weathering rate that does not compensate for increased cation uptake. We also know that N-deposition has led to accumulation effects in forest ecosystems, and that a continued change of species diversity of different kind is going on. N-deposition will also increase the risk for pathogenic attacks due to mineral imbalances in the trees, and contribute to a successively increased risk for leakage of nitrate also from forested land, making it even worse for the sea in the future. In order to understand future forest behaviour the models must include not only carbon but also nitrogen (Akselsson et al. 2007; Thornton et al. 2007).

Bouwman et al. (2009) made careful model estimates of N and phosphorus (P) use for the future, and concluded that in the most negative scenario we will increase the use of N by 50% up to 2050. The highest increase will be in Asia, Africa and South America. Today the level of N-deposition to forests in Central Europe clearly exceed the critical load estimates, and according to measurements in Sweden it has not been much reduced during the last 20 years, in spite several counteractions.

Concerning P, Bouwman et al. (2009) as well as many others, mean that the main P resources will be finished up to 2100. This is, however, a problem mainly for agricultural land and food production, probably not so much for forests and wood production.

We can foresee that CO_2 and N-emissions will not decrease during the coming decades, but most likely continue to increase. This might have detrimental effects on most plant species and especially on the vitality of trees in temperate zones. Recommendations for the future must be to increase forest plantations, preferably adapted to new climatic conditions, without the use of introduced species that may cause additional negative changes to both flora and fauna. It would be best to use regionally virgin provenances adapted to increased temperature. Another and most serious recommendation for the human society is of course to lower CO_2 as well as N-emissions strongly.

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