CO₂ Deficit in Temperate Forest Soils Receiving High Atmospheric N-Deposition

Evidence is provided for an internal CO₂ sink in forest soils, that may have a potential impact on the global CO₂-budget. Lowered CO₂ fraction in the soil atmosphere, and thus lowered CO₂ release to the aboveground atmosphere, is indicated in high N-deposition areas. Also at forest edges, especially of spruce forest, where additional N-deposition has occurred, the soil CO₂ is lowered, and the gradient increases into the closed forest. Over the last three decades the capacity of the forest soil to maintain the internal sink process has been limited to a cumulative supply of approximately 1000 and 1500 kg N ha⁻¹. Beyond this limit the internal soil CO₂ sink becomes an additional CO₂ source, together with nitrogen leaching. This stage of “nitrogen saturation” is still uncommon in closed forests in southern Scandinavia, however, it occurs in exposed forest edges which receive high atmospheric N-deposition. The soil CO₂ gradient, which originally increases from the edge towards the closed forest, becomes reversed.

INTRODUCTION

Root and microbial respiration implies that soils are a carbon dioxide (CO₂) source, constituting half of the CO₂ from respiration on the continents around the globe. An almost equivalent amount is released directly from terrestrial plants to the atmosphere (1, 2). CO₂ is transported to the atmosphere directly from the soil surface, or with drainage water to streams. The lowest CO₂ concentration in the soil atmosphere, even after total inhibition of CO₂ production in the soil, is considered to be that in the aboveground atmosphere, e.g. under frozen or dry conditions when no CO₂ is produced (3). However, low soil CO₂ concentrations during warm and wet conditions, even concentrations slightly below the aboveground atmospheric concentration, were recorded at some sites on the Swedish west coast where atmospheric N-deposition is high. These findings initiated the extensive 10-yr study reported here. In order to determine whether or not there was a soil process strong enough to decrease CO₂ emissions to the atmosphere, I collected 4594 soil atmosphere samples from 1992 through 2000, including one sampling occasion in June 2001 in the NW Pacific rainforest, Washington, USA.

MATERIALS AND METHODS

Sampling was carried out (number of samples within parentheses): Sweden (4200), Denmark (232), The Netherlands (55), USA (31), Norway (17). In addition, samples were also taken in Argentina, Brazil, Canada, The Czech Republic, Germany, Greece, Italy, and Polen (altogether 59). Samples were taken in spruce forest (3243), pine forest (253), deciduous forest (588), clearcut forest (227), grassland (57), agricultural land (196), and different types of vegetation, e.g. heathland (30). Sampling depth was generally 0–20 cm, but at some sites deeper layers were sampled, but less frequently. A total of 785 analyses of CO₂ were carried out in soil or the above soil atmosphere at the laboratory. Air samples were also analyzed (4). Site descriptions (fertilizer supply, N-leaching) are given in several research reports (5–12) and by I. Stjernquist (pers. comm. relating to the Konga experimental beech forest site).

At fertilized sites N added is included. Thirty-year N-accumulation was chosen, to include in the study the well-defined

Figure 1. The consequence of thinning for soil CO₂ concentration. A) CO₂ in the soil atmosphere at 20 cm in a spruce stand on peatland at Amböke, SW Sweden. Thinning resulted in a rise in summer groundwater levels from about 90 cm to 50 cm. Concurrently with the drastic increase in surficial soil CO₂, CH₄ concentrations up to more than 12% (v/v) were recorded at 40 cm. B) CO₂ at 0–40 cm depth at the Mahult spruce site one year before (1996), and the first (1997) and second year (1998) after thinning. Annual averages from 6, 7, and 10 complete profiles, respectively. Annual precipitation is indicated. The increase in CO₂ the first year after thinning can not be related to increased precipitation, and in the second year the effect of thinning is decreasing despite increased precipitation that year.
southern Swedish research sites that were started during the late 1960s, and since then have been administered by the Swedish University of Agricultural Sciences. A soil depth of 0–20 cm was generally selected to make the unsaturated layers at the sites comparable. Samples from deeper layers were not collected from all sites. A stainless steel tube, outside diameter 6 mm, with a perpendicular hole on the side close to the closed bottom end, was used for sampling. With a hand-operated vacuum pump the soil atmosphere was transferred into a connecting polybutene tube. The dead volume was first pumped out, and the polybutene tube was instantly closed at both ends. Samples were analyzed within 2 days, but usually on the same day (ocean samples within 1 week). The sampled soil atmosphere was taken from the tube with a syringe and immediately analyzed by gas-solid chromatography, separation on Haye Sep Q with a Varian 3300 instrument, and a Varian 4400 Integrator. Reference and carrier gases were from Air Liquide Gas Company.

RESULTS

To characterize the soil atmosphere that relates solely to N-deposition, long-term stable conditions were needed. Forest sites with anthropogenic disturbances other than high N-load, such as clearcutting, or even thinning—leading to higher groundwater level as a result of decreased evapotranspiration, and manifesting methane production in the summer (15) (Fig. 1), as well as drained and limed sites—were treated separately.

Forest edges receive considerably higher N-depositions compared to closed forests (16–18). The latter study (18) was on the same site as that studied by me, i.e. a soil CO₂-gradient from the forest edge (Stubbaröd in Fig. 4). Of the 45 sampling sites in undisturbed forests (Fig. 2) 5 were within 50 m from forest edges and N-depositions were adjusted to fit a gradient from 100% deposition at 50 m (closed forest) to 156% deposition 5 m from the forest edge (18).

The accumulated N-deposition on undisturbed sites showed a clear influence on CO₂ concentrations in the soil atmosphere (Fig. 2). However, high N-deposition does not only deplete soil CO₂ incidentally, but more importantly, soil CO₂ concentrations above the atmospheric concentration (the dominating situation) are lower than those resulting from respiration processes alone. In areas where cumulative atmospheric N-depositions—over the last 30 years—have reached 800–1000 kg ha⁻¹ yr⁻¹, soil CO₂ concentrations are less than half of those in low deposition sites. These conditions are now widespread and the indicated sink may have large-scale implications.

I assumed that the indicated CO₂-gradient in areas with low to high cumulative N-deposition should also occur locally where there is a similar N-deposition gradient. This deposition gradi-
ent occurs from the closed forest to the forest edge (18). Results from transects in central Sweden, where N-deposition to the closed forest is lower than in the south, support this hypothesis (Fig. 3).

A cumulative N-input of about 1000–1500 kg N deposited over a 30-yr period becomes critical. Beyond this N-accumulation level, soil CO$_2$ concentrations increase, concurrently with increasing nitrate leaching. During the course of the study this breakdown of the soil N- and CO$_2$-sequestration capacity was indicated at the Skogaby research site. Increased N-supply (from approx. 1500 to 1700 kg N deposited over 30 years) initiated a shift from low N-leaching into extreme leaching, simultaneously with an almost 3-fold increase in soil CO$_2$ (Fig. 2B). The same situation was also obvious for forest edges in a high N-deposition area in SW Sweden and in Denmark. Instead of the originally enforced soil CO$_2$ sink, the forest edge had become an increased CO$_2$ source (Fig. 4).

Low soil CO$_2$ concentrations were found even in the summer when intense soil respiration is expected. This could not be explained solely by decreased CO$_2$ production in the soil, as a result of, e.g., drying, or by day/night fluctuation of the aboveground CO$_2$, especially as the soil CO$_2$-depletion sometimes was more pronounced at deeper levels (19). Photosynthetic CO$_2$ consumption does not occur in the soil. To my knowledge, nitrification, a chemolithotrophic CO$_2$ consuming process, has not been considered as a potential CO$_2$ sink in forest soils. However, from wastewater-treatment processes it is well-known that nitrification alters alkalinity (CO$_2$ is removed and H$^+$ is added) (20).

Soil N-fertilization studies in the laboratory supported the results, but did not result in CO$_2$ concentrations below the aboveground air (21). Reduced soil CO$_2$ release as a result of applied inorganic N has been observed earlier. Interpretations for this phenomenon have involved: i) decreased microbial activity, explained by decreased C input or availability; ii) restriction of C-mineralization by high N-concentrations in the organic substrate; iii) disturbed balance between decomposers; iv) hampered production of enzymes; and v) formation of decomposing products being toxic or inhibitory (22–24). The impact of fertilization on soil respiration has also been reported as being low (25).

Nitrification has been demonstrated to occur even in acid forest soils (26–28). Nitrification in Swedish and Danish spruce forests was a chemolithotrophic process, with a high potential in the 10–50 cm soil layer (29). Liming stimulated nitrification, and reduced the CO$_2$ evolution rate, except when a nitrification inhibitor was used (23).

**DISCUSSION**

The present strong terrestrial, biospheric CO$_2$ sink, indicated by the $^{13}$C/$^{12}$C ratio in atmospheric CO$_2$ (30) is located in temperate latitudes where it became significant during the late 1980s (31). At that time considerable atmospheric N-deposition with subsequent soil N-accumulation had occurred in extensive temperate areas. The “missing sink” was related to N or CO$_2$ fertilization in Russian forests and North American forest regrowth. Biospheric CO$_2$ sinks as a result of terrestrial N-fertilization, have so far been related to increased forest growth (32, 33), or to forest regrowth on abandoned agricultural land (34), but have recently been questioned as the putative CO$_2$ sink in temperate forests (35).

This imbalance of the global carbon budget is estimated as 0.4–3.4·10$^9$ tonnes C yr$^{-1}$ (36–40). Estimates of the amount of CO$_2$ that could be assimilated, based on the energy yield from net nitrification (41), indicated that only a minor part of the missing CO$_2$ sink could be explained by this process. Recent findings from a study in western America (28) that gross nitrification in forest soils largely exceeds net nitrification, totally changed this view.

From areas with low N-deposition on undisturbed forests in New Mexico and Oregon, USA, Stark and Hart (28) reported gross nitrification up to 304 mg N m$^{-2}$ day$^{-1}$ during spring. This is in the magnitude of twice the total annual atmospheric N-deposition cycled in one day. A discrete estimate based on one third of that value (100 mg N m$^{-2}$ day$^{-1}$), lasting for 250 days per year, implies that 250 kg N ha$^{-1}$ would be nitrified annually. However, high atmospheric N-deposition areas in Europe receive, and retain, 10–20 times more N every year than do the American sites studied by Stark and Hart. A 10-fold increase in the N-cycling rate in these high N-deposition areas would result in 159 kg C ha$^{-1}$ yr$^{-1}$ (41). The efficiency of the nitrification reaction was set to 10%. Providing that 100 kg of the C reassimilated in the soil is preserved as organic material, and this process occurs in areas corresponding to half of the world’s moist temperate and boreal forest soils (only 8.4% of Haldridge’s Life Zones), gross nitrification would account for an annual sink 0.11·10$^9$ tonnes C (0.40·10$^9$ tonnes CO$_2$).

The American study (28) showed that NO$_3^-$ produced by nitrification is effectively assimilated by microorganisms. In this way, NO$_3^-$ leaching is prevented, which explains the effective N-retention in most forest soils. In the mature forest ecosystem, nitrogen is rapidly remobilized from the organic material (dead microbial biomass) and the NH$_4^+$ released makes repeated nitrification possible. According to my results and those of the American study (28), a soil “CO$_2$ pump” is operating, run by N-cycling in the forest soil. Every turn of the cycle implies CO$_2$-sequestration, resulting in the high potential soil CO$_2$-sink indicated where N-deposition has increased (Figs 2, 3).

High evapotranspiration is known to increase soil CO$_2$ production (3). However, the sites with highest evapotranspiration (Pacific rainforest) and lowest (two arctic sites in Scandinavia) all show high soil CO$_2$ concentrations (Fig. 2B). Atmospheric N-deposition is very low at these sites.

The results support the explanation that nitrogen cycling (nitrification, followed by microbial NO$_3^-$ uptake), causes the soil CO$_2$ sink. If production of CO$_2$ were disturbed or hampered by increased nitrogen supply, which was the alternative interpretation (22–24) this would probably enforce the sink, and not turn it into an increased CO$_2$ source when still more nitrogen is deposited. Whether the explanation is nitrification alone, or in combination with an inhibitory effect, N-deposition causes extensive reductions of forest soil CO$_2$ concentrations.

In summary, N-saturation causes increased N-leaching (42) and this coincides with loss of the internal soil CO$_2$ sequestra-
tion capacity, which increased CO$_2$ release from the soil. Effective N-cycling is still the most widespread process in forests (43). Therefore, the internal soil CO$_2$ sink still dominates. My results indicate that this sink can even be enforced extensively by additional N-deposition except in some very high deposition areas, e.g. in Europe, where N-saturation and subsequent increased CO$_2$ emissions from the soils are present. Support for this CO$_2$ sink in order to counteract the increase of CO$_2$ in the atmosphere, will need better knowledge of its areal distribution, and probably monitoring programs coupled with effective feedback mechanisms. When other aspects such as biodiversity are considered, increased N-deposition may be undesirable.

Using my findings some results, published quite recently, may be re-interpreted. Soil warming experiments in Massachusetts (44) and in northern Sweden (45) did not result in the expected increase in CO$_2$ release from the soil. Acclimatization of soil respiration was suggested to occur under temperature increase. According to my findings, the alternative interpretation may be that increased temperature, as expected, enhances soil respiration but also the internal soil CO$_2$ consumption process discussed here.

Within the comprehensive Skogaby project in southern Sweden, run from 1988 to 2001, the C and N soil pools were calculated. Instead of expected C/N ratios of 25 at the N-fertilized plots, and 30 at the control plots which received solely atmospheric deposition, the ratios calculated were unexpectedly high, 37 and 145, respectively. Overestimation of the soil carbon content, or underestimation of organic material mineralization was suggested (46). My hypothesis, implying repeated CO$_2$ uptake as a result of N-cycling, supports considerable soil carbon sequestration. It also appears that soil respiration is not equivalent to CO$_2$ released from the soil, especially where the internal soil CO$_2$ uptake is high as a result of high N-deposition.