Water regime of model forest ecosystems under elevated carbon dioxide and nitrogen deposition

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Abstract

Sixteen open-top chambers, each equipped with two non-weighable gravity-drained lysimeter compartments, were used to investigate the impacts of elevated atmospheric carbon dioxide concentration and nitrogen deposition on the water relations and growth of young beech-spruce model forest ecosystems on two soils, an acidic sandy loam and a calcareous loamy sand. The soils were repacked on top of a drainage layer. Four combinations of two CO_2 and two N treatments were applied in four replicates each: ambient vs. elevated (+220 mg kg^{-1}) CO_2 and low (2.5 – 7 kg N ha^{-1} a^{-1}) vs. high (25-70 kg N ha^{-1} a^{-1}) N deposition.

Treatment effects were very different for the two soils. On the acidic soil, evapotranspiration was reduced by approximately. 8% under elevated CO_2, while growth showed a slight, but not significant tendency of increase. High N deposition on the other hand not only led to a strong increase in new leaf growth, but also to an increased evapotranspiration. Water use efficiency was increased in both treatments. In combination the effects of CO_2 and N on evapotranspiration and growth were approximately equivalent to the sum of the single treatments. On the calcareous soil, elevated CO_2 tended to increase evapotranspiration and strongly enhanced growth, whereas N had none or a small negative effect on new leaf growth and evapotranspiration and decreased subsoil root growth at both CO_2 concentrations, in contrast to the N treated acidic soil. The differences in the treatment effects are consistent with the hypothesis that growth on the acidic soil was N limited, while on the calcareous soil it was not.

Keywords: soil water regime, forest ecosystems, climate change, evapotranspiration

Introduction

Apart from its greenhouse effect rising atmospheric CO_2 concentration may also have profound direct impacts on ecosystems. As CO_2 uptake by plants is directly coupled to transpirational water loss through stomatal apertures, elevated atmospheric CO_2 allows plants to save water for the same amount of carbon fixation, i.e. to increase their water use efficiency (WUE). On an ecosystem level, this can result in reduced transpiration or, enhanced growth or a combination of both. The final response does not only vary with plant species, but also with environmental conditions, including nutrient availability. Stimulation of growth may be even so strong that water consumption on the whole is increased although it is decreased per unit leaf area (Field *et al.*, 1995). Nutrient limitations appear to be one of the key factors in determining the response.

Because of the important role of forests in global ecological and hydrological processes, effects of elevated atmospheric CO_2 on trees are of particular concern. Although the effects of elevated atmospheric CO_2 on tree water relations have been studied extensively (for review see Saxe *et al.,* 1998), most data have been obtained from pot experiments with individual tree seedlings, where growth occurs without competition with other plants, but under highly artificial rooting conditions. Studies of CO_2 effects on forest water regime under natural stand conditions are mostly based on instantaneous tree physiological measurements, and due to the complexity of highly heterogeneous and variable site conditions they are also in general not well suited to analyse the influence of individual site factors.

Given such problems, it is not surprising that there is a lack of studies in which the influence of soil on CO_2 effects on tree water relations has been investigated on an eco-system level. As many forests grow on nutrient-poor soils and are not artificially fertilized, natural soil fertility may be much more important than in intensively managed agricultural systems. For the same reasons, also atmospheric nitrogen deposition must be considered as important factor in forest responses to elevated atmospheric CO_2 concentrations.

Addressing the lack of pertinent studies, we performd a factorial lysimeter experiment with model ecosystems in which the water relations of mixed stands of young beech and spruce trees were investigated on two diffferent soils under two levels of atmospheric CO_2 concentration and two levels of nitrogen deposition. The study was part of a larger project as described by Landolt *et al.* (1997). A comprehensive synthesis of the various projects has been edited by Brunold *et al.* (2001).

Materials and Methods

The experiments were performed in the open-top chamber facility of the Swiss Federal Institute of Forestry, Snow and Landscape Research, Birmensdorf (Switzerland), which is situated close to the city of Zurich at 450 m above sea-level Each of the 16 hexagonal chambers was equipped with two non-weighable lysimeter compartments of 1.5 m depth and 3 m^2 surface area.

On top of a 0.5 m quartz filter packing, two different forest soils from the vicinity of Zurich were filled into the two lysimeter compartments of each chamber in spring 1994. One soil was a calcareous loamy sand originating from a Calcaric Fluvisol, the other an acidic sandy loam deriving from a Haplic Alisol. Corresponding to the lack of distinct soil horizons in the sampled fluvisol, the calcareous soil was filled into the lysimeter in one layer, whereas in the case of the acidic soil a 0.4 m topsoil layer and a 0.6 m subsoil layer were packed separately in accordance with the original layering of the material. Soil properties are given in Table 1.

On each lysimeter, 8 seedlings of Norway spruce (*Picea abies*), 8 saplings of beech (*Fagus sylvatica*) and several individuals of five understorey species (*Carex sylvatica, Geum urbanum, Hedera helix, Ranunculum ficaria, and Viola sylvatica*) were planted in autumn 1994.

The four combinations of CO_2 and N treatments are denoted as 'control', '+CO_2', '+N' and '+CO_2xN'. Ambient air was supplied through wide porous tubes along the lower parts of the chamber walls. In the '+CO_2' and '+CO_2xN' treatments 220 mg kg^{-1} CO_2 were added to the ambient air. In the '+N' and '+CO_2xN' treatments, total nitrogen

input was increased by adding NH_4NO_3 to the irrigation water giving an input of 25 (1995), 50 (1996), 70 (1997) and 65 (1998) kg N ha^{-1} a^{-1}. In the 'control' and '+CO_2' treatments total N input was 2.5 (1995), 5 (1996), 7 (1997) and 6.5 (1998) kg N ha^{-1} a^{-1}. Each of the four treatments was applied in four replicates, arranged according to a 4x4 Latin square scheme.

Table 1 Soil properties.

Property		Acidic soil		Calcareous soil
		Topsoil	Subsoil	
pH		3.7	3.8	7.0
Organic matter content		1.8%	0.1%	1.2%
Carbonate content		-	-	19.2%
Porosity		0.54	0.43	0.56
Mass fraction of				
-sand		0.55	0.55	0.84
- silt		0.29	0.27	0.10
- clay		0.16	0.18	0.06
Ca	cmol kg^{-1}	14	n.d.	124
K	cmol kg^{-1}	1.17	n.d.	0.57
P	cmol kg^{-1}	2.1	n.d.	6.5
N exchangeable	mg kg^{-1}	2.4	n.d.	3.8

Irrigation water was supplied equally in all treatments by sprinklers located above the canopy. In order to prevent uncontrolled water input the transparent roofs of the chambers were automatically closed during rainfall. Irrigation was adapted to the actual water demand of the vegetations, except for two periods in 1997 in which irrigation was stopped or kept below demand for three to four weeks. Drainage water was conducted through three outlets at the bottom of each lysimeter and collected in plastic containers, which were emptied at weekly intervals. For monitoring soil water contents and potentials, TDR probes and tensiometers were installed centering at 25, 50 and 75 cm depth.

All trees were harvested at the end of the four-year experiment in autumn 1998 and analyzed biometrically as described by Bucher-Wallin *et al.,* (2000).

Results

In the third and fourth year of the experiment, when canopies were closed, clear effects on evapotranspiration became apparent. These were almost opposite to each other in sign not only between the two treatments for a given soil, but also between the two soils for a given treatment (Figure 1). On the acidic soil, increased nitrogen deposition significantly enhanced evapotranspiration, whereas elevated CO_2 decreased it. On the calcareous soil, where evapotranspiration was in average around 25% higher than on the acidic soil, effects were much smaller. Evapotranspiration slightly increased under elevated CO_2 (not significantly in 1998), while under the increased nitrogen

deposition it slightly decreased in 1997 and showed no effect in 1998. The effects of the combined treatments were approximately equivalent to the sum of the effects observed in the single treatments, which means that no interactions between the two treatments were found

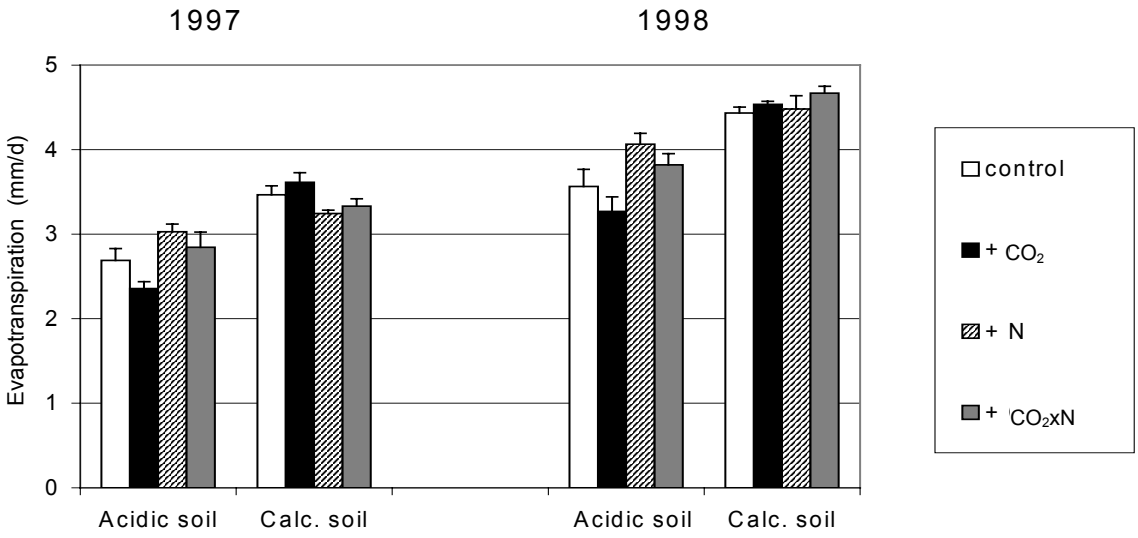

Figure 1 Average rate of evapotranspiration for the periods 1 April – 31 August of the third (1997) and fourth year (1998) of the experiment (treatment means + standard errors). Significance level P of the main effects: <0.01 (1997) and <0.05 (1998) for CO_2 effect and <0.001 (1997 and 1998) for N effect on acidic soil; <0.05 (1997) and 0.1 (1998) for CO_2 effect and <0.05 (1997) for N effect on calcareous soil. No N effect in 1998 on calcareous soil.

In average over the two years, the strongest effect measured was the increase of evapotranspiraton by 16% on the acidic soil due to the nitrogen treatment. Although the effects thus were rather small, they were very consistent not only between years, but also over shorter time periods. This was not only revealed by bi-weekly water balances, but also by the monitoring of soil water tensions and water contents (Bucher-Wallin, 2000; Sonnleitner *et al.,* 2001). The latter data also indicate that the measured increase of evapotranspiration under elevated CO_2 on the calcareous soil was a real effect in 1998 as in the year before and not just due to statistical scatter in the data.

The two treatments, +CO_2 and +N, also had very different effects on growth as can be inferred from Figures 2 and 3. Elevated CO_2 strongly stimulated growth on the calcareous soil, but not on the acidic soil. Sonnleitner. (2001) reported a slightly enhanced root growth in 1997 under elevated CO_2 on the acidic soil. This effect was not highly significant ($P < 0.05$), however, and was not confirmed in the following year. Increased nitrogen deposition, on the other hand, strongly stimulated above ground growth on the acidic soil and to a much lesser degree also root growth, but had no positive growth effect on the calcareous soil. The slight increase in leaf biomass production in combination with CO_2 shown by Figure 2 was not significant. Root growth was rather decreased than increased by nitrogen deposition on the calcareous

soil as Figure 3 shows, in agreement with Sonnleitner *et al.* (2000) who found a clearly reduced subsoil root development in 1997 under high nitrogen deposition in this soil.

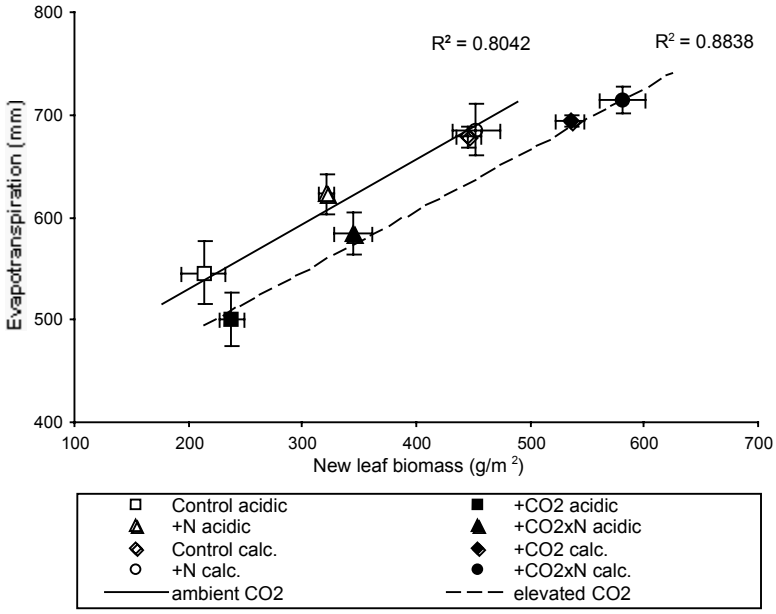

Figure 2 Relationship between new leaf biomass growth until harvest in September 1998 and total evapotranspiration in the period 1 April-31 August 1998. Lines represent linear regressions, points treatment averages, and bars standard errors.

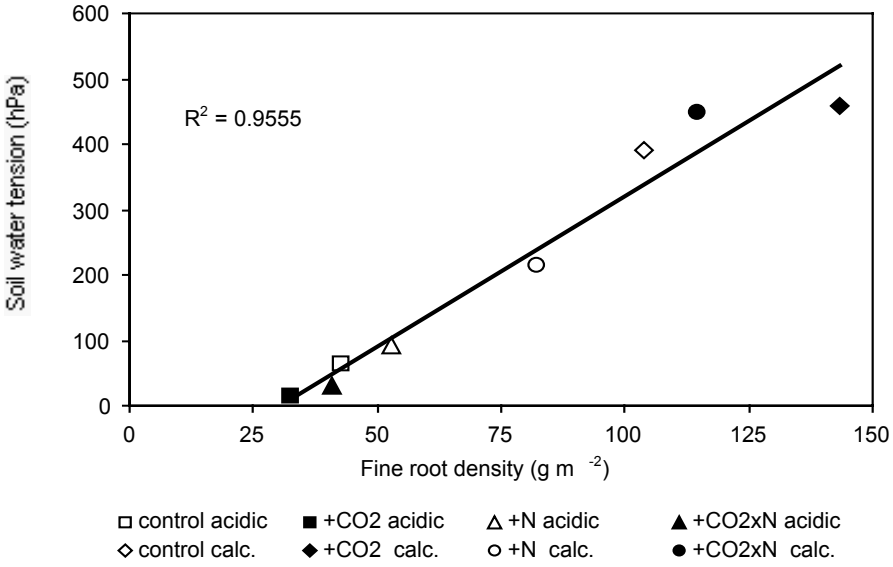

Figure 3 Relationship between mean density of fine roots harvested in the subsoil (0.5-1 m depth) at the end of the experiment and mean soil water tension measured at 75 cm depth in July and August 1998.

Although the effects on water consumption and growth were quite different on the two soils, elevated CO_2 increased water use efficiency (defined here as the ratio

between new leaf biomass production and evapotranspiration) on both. Nitrogen increased water use efficiency only on the acidic soil, where it had a strong growth effect. On the calcareous soil, water use efficiency remained unaffected by nitrogen, as it had neither a significant effect on water consumption, nor on leaf biomass. Figure 2, in which evapotranspiration is plotted as a function of leaf biomass production, shows that the different nitrogen treatments at ambient CO_2 concentration fall onto one line and those at elevated CO_2 onto another, independent of soil type. This result means that the increase in water consumption was the same for the same increment of leaf biomass at a given CO_2 concentration. It suggests that the nitrogen effect on water consumption may simply be a function of its effect on growth. In contrast, the CO_2 effect cannot be understood as only a growth effect, because increased CO_2 in addition also led.to a parallel shift of this line towards higher water use efficiency.

Another interesting relationship was found between fine root density and soil moisture depletion during the vegetation period, expressed in terms of the mean of soil water tensions recorded in July 1998. As Figure 3 shows, the eight treatment combinations approximately fall upon the same line. This relationship suggests that rooting density may have been the main factor accounting for the different degrees of soil water exploitation in the various treatments.

Discussion and Conclusions

As the measured water tensions did not indicate the occurrence of severe water stress at any time during the experiment, limitation in water supply can hardly account for the observed differences in growth between the treatments. The strong response on nitrogen indicates that growth on the acidic soil was nitrogen-limited. In contrast, the lack of such a response under ambient as well as elevated CO_2 shows that nitrogen was not at all a limiting factor in the calcareous soil. The observation that additional nitrogen allowed the trees on this site even to reduce their investments of assimilates into root growth gives further evidence for this conclusion. As a consequence of the nitrogen limitation, increased availability of CO_2 could not be utilized to enhance biomass production significantly at the ecosystem level, and therefore was used to save on soil water resources. On the calcareous soil, elevated CO_2 produced a strong fertilizer effect. Obviously, growth was primarily limited by CO_2 availability, while nitrogen and other essential nutrients were in sufficient supply. With no other growth limitations, the increased CO_2 availability could be translated entirely into additional assimilation, and thus also water consumption was rather increased than decreased. The results further suggest that nitrogen was not the only factor making the difference between the two soils, because even the high nitrogen input of the +N treatment growth was not sufficient to reach the growth observed on the the calcareous soil. In summary, the results show that an ecosystem can respond very differently to changes in CO_2 availability depending on conditions such as nitrogen supply and that soil plays a key role in determining that response. This result is important with respect to possible ecological and hydrological consequences of globally increasing atmospheric CO_2 concentrations.

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