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“Research, monitoring and modelling in the study of climate change and air pollution impacts on forest ecosystems”

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Effects of increasing CO₂ on trees and intensively monitored plots: research needs in view of future ecosystem studies

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The intensively monitored plots in Europe have offered a lot of information with regard to the dynamics of forest ecosystems. A large stock of data is already available as an input to ecological models. The carbon sequestration challenge is a little different from others. It requires long-term studies and additional information from what already exists. So far, apart from the determination of organic C in soils, research in the intensively monitored plots has mainly focused on above ground processes, *i.e.*, crown assessment, phenology, deposition, litterfall, tree growth, and foliar chemistry. All these parameters are valuable and will continue to be so. However, according to the latest literature reviews on the subject, the key to understanding the reaction of trees to climate change lies in the dynamics of belowground processes. Information is needed on nitrogen mineralization rates, soil respiration rates and labile carbon forms in soils. If we take into account that countries pay for their carbon emissions and are paid for carbon sequestration, a research like this can be worth doing. Most importantly, the ecological models can be enriched and therefore be more precise in predicting tree response to climate change.

Keywords: Forest, Atmospheric CO₂, Intensively monitored plots

Introduction

There is a growing increase in the impact of elevated atmospheric CO₂ on forest trees and forest ecosystems. This is not surprising as forests cover some 27% of the total land surface but account for some 70% of terrestrial net primary production (Melillo et al. 1993). Moreover, more than 85% of the total plant C on earth and between 60-70% of the total soil C is contained in forests (Dixon et al. 1994). The atmospheric concentration of

CO₂ is currently increasing at the rate of 3.3 billion tons of C per year (IPCC 2001). Very good reviews have been published about the consequences of elevated atmospheric CO₂ on forests (Ceulemans & Mouseau 1994, Saxe et al. 1998, Ceulemans et al. 1999, Karnosky 2003, Lal 2005). Ceulemans et al. (1999) argue that the question is not so much by what we do not know, but rather how to best integrate our knowledge in order to predict the performance and productivity of future ecosystems to global climatic changes. Newman et al. (2006) have the opinion that our current ability to detect and predict changes in forest ecosystem productivity is constrained by several limitations. These include a poor understanding of belowground productivity, the short duration of most analyses, and a need for greater examination of species or community-specific variability in productivity studies. From studies to date, we know that the life-long above ground growth response of forest trees cannot be accurately predicted from short-term experiments (Norby et al. 1999). Karnosky (2003) suggests long-term studies using free-air CO₂ enrichment (FACE) technologies or forest stands around natural CO₂

vents so as to increase the knowledge base on forest ecosystem responses to elevated atmospheric CO₂. There is no doubt that FACE experiments can offer valuable information. However, there are some shortcomings with those experiments. First is the representativity. If the FACE experiments try to cover the whole range of forest ecosystem types, the cost will be tremendously high. The second is that FACE experiments will have a higher rate of CO₂ enrichment than the actual rising rate of CO₂. Forest stands around natural CO₂ vents are rather limited. The establishment of new plots in natural atmosphere has, of course, the disadvantage of the very long-term expectancy of conclusions. Hopefully, there are already experimental plots, which have a past of ecological measurements. These are the intensively monitored plots (800 in total) which were installed in Europe under the auspices of the ICP-Forests (2010). Those plots were installed when concern about the threat of atmospheric pollution on forest vitality was widespread. In this work I will try to stress the importance of keeping monitoring these plots. More specifically, I will focus on the potential contribution the intensively monitored plots can offer to meet the knowledge gaps with regard to tree responses to elevated atmospheric CO₂. These knowledge gaps were set by Karnosky (2003). The measures suggested concern long-term monitoring so they must be as cost efficient as possible.

Tree growth

It has been found that short-term assimilation of CO₂ is significantly stimulated by increased CO₂ in nearly all plant species (Saxe et al. 1998, Luo et al. 1999). However, in the longest study (25-30 years) of continuous exposure of forest trees to elevated atmospheric CO₂ with forest stands of holm oak growing in the vicinity of two natural CO₂ springs in Italy, it was found that the trees showed a moderate, age dependent increase in stem biomass production, but had significantly lower biomass of 6-year-old branches, decreased branching, and lower leaf area per unit branch biomass, compared to control trees at a nearby site (Hättenschwiler et al. 1997). In the intensively monitored plots growth has been measured since 1995. At that time tree diameter was measured either with measuring tapes or calipers. Recently, during the Pan European FutMon project (<http://www.futmon.org/>) some diameters were measured with girth bands. These bands are relatively cheap and very accurate. This kind of measurement can be extended in all plots to include many more trees. In some years there will be valuable results all over Europe.

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Water balance

Long-term studies of forest trees in an enriched atmosphere with CO₂ have shown a significant 21% decrease in stomatal conductance (Medlyn et al. 2001). However, as tree biomass increases the question remains whether trees use more or less water even if stomatal conductance decreases. The installation of soil moisture sensors in many plots help in the calculation of the whole water balance in forest stands. The actual magnitude of transpiration cannot be calculated but a comparison between forest stands can be made. For instance, for the same amounts of rainfall and interception the stand with the less water loss in drainage (assuming there is no surface runoff) will have a higher transpiration rate. The soil water holding capacity of each stand will be a covariate in the statistical comparison.

Soils

An important aspect that has not been tackled so far by the ICP-Forests projects is the form of C in soils. Elevated atmospheric CO₂ will bring about a stimulation of soil respiration, which can be much higher than the enhancement of root biomass (Cheng & Johnson 1998). A major consequence of the increase in microbial activity and consequently in CO₂ production is a potential negative effect on the accumulation of organic C in soils and thus C potential sequestration of soils (Hungate et al. 2003). However, there is a plateau beyond which organic matter cannot be easily attacked by microbes. Mineralization of soil organic matter strongly depends on the size of the labile C pool in addition to the effects of the microbial community and abiotic environmental conditions like temperature and moisture (Davidson et al. 1998). A simple method to measure the labile C pool in soils is by water extraction (Jiang & Xu 2006). Although water extractable organic C makes up only a small portion of total soil organic matter (usually less than 1% - Chantigny 2003), it might provide a measure of microbially available C. Zhao et al. (2008) found a strong relationship between water extractable organic C and the rates of C mineralization using arable and forest soils.

In the intensively monitored plots the two

soil surveys have a distance of 10 years from each other (1997 and 2007). Most countries, if not all, have stored the samples so they can be reanalyzed. If a third survey takes place in another 10 years, there will be a set of data with the amount of microbially available C covering a time space of 30 years. Comparisons can be made having in mind a fourth or fifth survey for the next generations.

Plant nutrition and nutrient cycling

The growth response of forest plants to the rising concentrations of CO₂ depends on their ability to acquire soil nutrients and water (Hättenschwiler & Körner 1996). Nutrient imbalances are reflected in foliar analysis. Every two years foliar analysis is carried out in all plots. A valuable data bank has been formed and should be enriched in the following years.

It has been well documented that the nitrogen level in the foliage of trees growing under elevated atmospheric CO₂ generally decreases (Lindroth et al. 1993). As an example for repeated measures analyses, Fig. 1 shows N concentrations in fir foliage over time in one of the intensively monitored plots in Greece (Michopoulos et al. 2010). In that particular case no significant changes were observed.

Nitrogen concentrations also decrease in litterfall (Norby et al. 2001). By contrast to N concentration, the quantity of litterfall increases 20-30% under elevated CO₂ (De Lucia 1999). It is not known how nutrient mineralization will change due to the higher quantity of CO₂ in soil. In the intensively monitored plots litterfall is monitored. Litterfall quantities are measured and elemental analyses are carried out. A simple test is a time series comparison between the successive N concentrations in foliage and foliar litterfall.

If the N content in litterfall decreases so must decrease the litter decomposition rates and the N mineralization rates. Both of them can be measured with the classic method of the litterbags technique. This is a relatively easy technique that can be employed in the future.

Belowground carbon allocation

Allocation of C to belowground plant structures often equals or exceeds aboveground litterfall C and aboveground respiration in forest ecosystems, making it the single most important fate for gross primary productivity (Kimmins 1996). Despite its importance, total belowground allocation (TBCA) remains poorly quantified because it is difficult to quantify root and mycorrhizal processes by any method (Hanson et al. 2000, Hendrick & Pregitzer 1993). If growth is enhanced, there will be more C input into the soil. Therefore, a major indirect response to an increase in atmospheric CO₂ consists in the greater below-ground C allocation through root exudation and turnover, which is likely to lead to changes in the size and the activity of soil microflora (Körner 2000).

In the absence of direct measurements of TBCA, Raich & Nadelhoffer (1989) and Davidson et al. (2002) proposed the following equation (eqn. 1):

$$TBCA = \text{Soil respiration } C \\ - \text{Aboveground Litterfall } C$$

where soil respiration is the sum of root respiration, root litter C decomposition and aboveground litter C decomposition.

A critical assumption of this approach to estimate TBCA is that the ecosystem is at a steady state, which means that the annual inputs of C below ground are equal to annual rates of decomposition.

If the system is not at a steady state the previous equation becomes (eqn. 2):

$$TBCA = R_{\text{soil}} - C_{\text{litterfall}} + \Delta C_{\text{litter}} \\ + \Delta C_{\text{soil}} + \Delta C_{\text{root}} + C_{\text{export}}$$

where ΔC_{soil} , ΔC_{litter} , ΔC_{root} are the changes in C stocks of mineral soil, forest floor and root biomass, respectively, and C_{export} is C loss through leaching. From the above equation the parameters R_{soil} , $C_{\text{litterfall}}$ and C_{export} in soil solution can be measured continuously in the intensively monitored plots. ΔC_{soil} and ΔC_{litter} can be measured in the following soil survey and compared with the survey in 2007. ΔC_{root} can be calculated from an equation between ABD (aboveground biomass density) in Mg ha⁻¹ and RBD (root biomass density) also in Mg ha⁻¹.

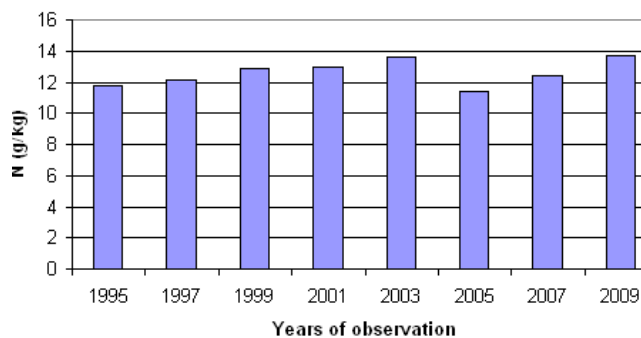
Cairns et al. (1997) used the following equation (eqn. 3):

$$RBD = e^{-1085 - 0.926 \ln(ABD)}$$

The above equation was based on 160 studies covering tropical temperate and boreal forests. The use of this equation is encouraged by other workers (Brown 2002).

The total above ground biomass includes foliage apart from woody biomass. There are

Fig. 1 - Nitrogen concentration in current year's needles of fir (*Abies borisii regis*) in Greece.



equations connecting foliage and tree diameters and heights for the main forest species (Kittredge et al. 1994), so that all components of the equation can be found.

In order to apply the above equations, the soil respiration rates have to be measured. It is probably the only expensive measurement, but it will help in drawing valuable conclusions, as soil respiration depends on soil moisture and temperature repeated measures have to be taken in time and space. Vincent et al. (2006) used soil respiration chambers on which a portable infrared gas analyser was connected. They measured respiration in daytime during the growth period in a temperate deciduous forest. Raich (1998) measured soil respiration with the soda-lime technique in three Hawaiian rain forests in a whole year period. The soil respiration fluxes should be expressed as the litterfall fluxes, *i.e.*, in $\text{kg ha}^{-1} \text{yr}^{-1}$. So a whole year of measurements is necessary. The number of samplers (chambers) depends on the variability of respiration rates and the required probability level. A trial can be carried out with a limited number of samplers after which the required sample size for a given confidence interval can be calculated according to statistical formulas (Weiss 1989).

In my opinion, the first simpler equation may be used in most cases and the second one may be applied when there is a third soil survey in the intensively monitored plots.

Phenology

Phenology is the study of the periodicity of leafing, flowering and fruiting in plants in relation to climate and other environmental factors. There is the hypothesis that elevated CO_2 can affect development of leaf area in the spring so that trees could potentially benefit from an earlier onset of C assimilation at the start of the growing season. This could be an important factor in the expansion of tree populations into areas currently too cold for their growth (Saxe et al. 1998). Phenological observations are carried out regularly in the intensively monitored plots and if leaf area increases that will be written down. What I now suggest is the extension of phenological observations to mycorrhizal fungi. This is crucial because the plants's ability to acquire soil resources in an elevated CO_2 environment is mediated by symbiotic associations with mycorrhizal fungi. A new distribution of mycorrhizal fungi may not be beneficial to plants as the plant-fungi symbiosis was evolved over time due to natural selection.

Conclusions

The intensively monitored plot can be a valuable tool in assessing the impact of elevated CO_2 on forests. The activities already existing should be complemented by the following actions:

1. Tree growth is suggested to be monitored with girth band in all plots;
2. A third soil survey must be carried out. In this survey, together with stored samples of the previous ones, the labile C should be determined by water extraction.
3. Soil respiration must be measured so as to draw conclusions on the C allocated belowground.
4. Organic matter mineralization rates should be determined in all plots.
5. Phenology observations must include the distribution of mycorrhizal fungi.

References

- Brown S (2002). Measuring carbon in forests: current status and future challenges. *Environmental Pollution* 116: 363-372. - doi: [10.1016/S0269-7491\(01\)00212-3](https://doi.org/10.1016/S0269-7491(01)00212-3)
- Cairns MA, Brown S, Helmer EH, Baumgardner GA (1997). Root biomass allocation in the world's upland forests. *Oecologia* 111: 1-11. - doi: [10.1007/s004420050201](https://doi.org/10.1007/s004420050201)
- Chantigny MH (2003). Dissolved and water-extractable organic matter in soils: a review on the influence of land use and management practice. *Geoderma* 113: 357-380. - doi: [10.1016/S0016-7061\(02\)00370-1](https://doi.org/10.1016/S0016-7061(02)00370-1)
- Cheng WX, Johnson DW (1998). Elevated CO_2 , rhizosphere processes, and soil organic matter decomposition. *Plant and Soil* 202: 167-174. - doi: [10.1023/A:1004315321332](https://doi.org/10.1023/A:1004315321332)
- Ceulemans R, Mousseau M (1994). Effects of elevated atmospheric CO_2 on woody plants. *New Phytologist* 127: 425-446. - doi: [10.1111/j.1469-8137.1994.tb03961.x](https://doi.org/10.1111/j.1469-8137.1994.tb03961.x)
- Ceulemans R, Janssens IA, Jach ME (1999). Effects of CO_2 enrichment on trees and forests: Lessons to be learned in view of future ecosystems studies. *Annals of Botany* 84: 577-590. - doi: [10.1006/anbo.1999.0945](https://doi.org/10.1006/anbo.1999.0945)
- Davidson EA, Belk E, Boone RD (1998). Soil water content and temperature as independent or confounded factors controlling soil respiration in a temperate mixed hardwood forest. *Global Change Biology* 4: 217-227. - doi: [10.1046/j.1365-2486.1998.00128.x](https://doi.org/10.1046/j.1365-2486.1998.00128.x)
- Davidson EA, Savage K, Bolstad P, Clark DA, Curtis PS, Ellsworth DS, Hanson PJ, Law BE, Luo Y, Pregitzer KS, Randolph JC, Zak D (2002). Belowground carbon allocation in forests estimated from litterfall and IRGA-based soil respiration measurements. *Agricultural and Forest Meteorology* 113: 39-51. - doi: [10.1016/S0168-1923\(02\)00101-6](https://doi.org/10.1016/S0168-1923(02)00101-6)
- De Lucia EH (1999). Net primary production of a forest ecosystem with experimental CO_2 enrichment. *Science* 284 (5417): 1177-1179. - doi: [10.1126/science.284.5417.1177](https://doi.org/10.1126/science.284.5417.1177)
- Dixon RK, Brown S, Houghton RA, Solomon AM, Trexler MC, Wisniewski J (1994). Carbon pools and flux of global forest ecosystems. *Science* 263: 185-190. - doi: [10.1126/science.263.5144.185](https://doi.org/10.1126/science.263.5144.185)
- Hanson PJ, Edwards NT, Garten CT, Andrews JA (2000). Separating root and soil microbial contri-

- butions to soil respiration: a review of methods and observations. *Biogeochemistry* 48: 115-146. - doi: [10.1023/A:1006244819642](https://doi.org/10.1023/A:1006244819642)
- Hättenschwiler S, Körner C (1996). System-level adjustment to elevated CO_2 in model spruce ecosystems. *Global Change Biology* 2: 377-387. - doi: [10.1111/j.1365-2486.1996.tb00088.x](https://doi.org/10.1111/j.1365-2486.1996.tb00088.x)
- Hättenschwiler S, Miglietta F, Raschi A, Körner C (1997). Morphological adjustment of mature *Quercus ilex* trees to elevated CO_2 . *Acta Oecologica* 18: 361-365. - doi: [10.1016/S1146-609X\(97\)80026-4](https://doi.org/10.1016/S1146-609X(97)80026-4)
- Hendrick RL, Pregitzer KS (1993). The dynamics of fine root length, biomass and nitrogen content in two northern hardwood ecosystems. *Canadian Journal of Forest Research* 23: 2507-2520. - doi: [10.1139/x93-312](https://doi.org/10.1139/x93-312)
- Hungate BA, Dukes JS, Shaw MR, Luo Y, Field CB (2003). Atmospheric science: nitrogen and climate change. *Science* 302: 1512-1513. - doi: [10.1126/science.1091390](https://doi.org/10.1126/science.1091390)
- ICP-Forests (2010). ICP-Forests: International Co-operative Programme on Assessment and Monitoring of Air Pollution Effects on Forests. [online] URL: <http://www.icp-forests.org>
- IPCC (2001). Climate change: the scientific basis. Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK.
- Jiang PK, Xu QF (2006). Abundance and dynamics of soil labile carbon pools under different types of forest vegetation. *Pedosphere* 16: 505-511. - doi: [10.1016/S1002-0160\(06\)60081-7](https://doi.org/10.1016/S1002-0160(06)60081-7)
- Karnosky DF (2003). Impacts of elevated CO_2 on forest trees and forest ecosystems: knowledge gaps. *Environment International* 29: 161-169. - doi: [10.1016/S0160-4120\(02\)00159-9](https://doi.org/10.1016/S0160-4120(02)00159-9)
- Kimmins JP (1996). Forest ecology. A foundation for sustainable management. Prentice Hall, New Jersey, USA.
- Kittredge JM, Rimmer JH, Looney MA (1994). Validation of the rockport fitness walking test for adults with mental retardation. *Med Sci Sports Exerc* 26 (1): 95-102. [online] URL: <http://www.ncbi.nlm.nih.gov/pubmed/8133745>
- Körner C (2000). Biosphere responses to CO_2 enrichment. *Ecological Applications* 10: 1590-1619. - doi: [10.1890/1051-0761\(2000\)010\[1590:BRTCE\]2.0.CO;2](https://doi.org/10.1890/1051-0761(2000)010[1590:BRTCE]2.0.CO;2)
- Lal R (2005). Forest soils and carbon sequestration. *Forest Ecology and Management* 220: 242-258. - doi: [10.1016/j.foreco.2005.08.015](https://doi.org/10.1016/j.foreco.2005.08.015)
- Lindroth RL, Kinney KK, Platz CL (1993). Responses of deciduous trees to elevated atmospheric CO_2 : productivity, phytochemistry and insect performance. *Ecology* 74: 763-777. - doi: [10.2307/1940804](https://doi.org/10.2307/1940804)
- Luo Y, Reynolds J, Wang YP, Wolfe D (1999). Research for predictive understanding of plant responses to elevated CO_2 . *Global Change Biology* 5: 143-156. - doi: [10.1046/j.1365-2486.1999.00215.x](https://doi.org/10.1046/j.1365-2486.1999.00215.x)
- Medlyn BE, Barton CMV, Broadmeadow MSI, Ceulemans R, De Angelis P, Forestreuter M, et al. (2001). Stomatal conductance of forest species after long-term exposure to elevated CO_2 concentrations: a synthesis. *New Phytologist*

- 149: 247-264. - doi: [10.1046/j.1469-8137.2001.00028.x](https://doi.org/10.1046/j.1469-8137.2001.00028.x)
- Melillo JM, McGuire DA, Kicklighter DW, Moore B, Vorosmarty CJ, Schloss AL (1993). Global climate change and terrestrial net primary production. *Nature* 363: 234-240. - doi: [10.1038/363234a0](https://doi.org/10.1038/363234a0)
- Michopoulos P, Economou A, Karetos G, Tsagari K, Voulala M, Bourletsikas A, Kaoukis, K (2010). Nitrogen in a fir stand. Is there any risk of saturation? 13th Greek Soil Science Congress, pp. 389-397. [In Greek with an english abstract].
- Newman GS, Arthur MA, Muller RN (2006). Above and below ground net primary production in a temperate mixed deciduous forest. *Ecosystems* 9: 317-329. - doi: [10.1007/s10021-006-0015-3](https://doi.org/10.1007/s10021-006-0015-3)
- Norby RJ, Wullschlegel SD, Gunderson CA, Johnson DW, Ceulemans R (1999). Tree responses to rising CO₂ in field experiments: implications for the future forest. *Plant Cell Environment* 22: 683-714. - doi: [10.1046/j.1365-3040.1999.00391.x](https://doi.org/10.1046/j.1365-3040.1999.00391.x)
- Norby RJ, Cotrufo MF, Ineson P, O'Neil EG, Canadell JG (2001). Elevated CO₂, litter chemistry, and decomposition: a synthesis. *Oecologia* 127: 153-165. - doi: [10.1007/s004420000615](https://doi.org/10.1007/s004420000615)
- Raich JW (1998). Aboveground productivity and soil respiration in three Hawaiian rain forests. *Forest Ecology and Management* 107: 309-318. - doi: [10.1016/S0378-1127\(97\)00347-2](https://doi.org/10.1016/S0378-1127(97)00347-2)
- Raich JW, Nadelhoffer KJ (1989). Belowground carbon allocation in forest ecosystems: global trends. *Ecology* 70: 1346-1354. - doi: [10.2307/1938194](https://doi.org/10.2307/1938194)
- Saxe H, Ellsworth DS, Heath J (1998). Tree and forest functioning in an enriched CO₂ atmosphere. *New Phytologist* 139: 395-436. - doi: [10.1046/j.1469-8137.1998.00221.x](https://doi.org/10.1046/j.1469-8137.1998.00221.x)
- Vincent G, Shahriari AR, Lucot E, Badot PM, Epron D (2006). Spatial and seasonal variations in soil respiration in a temperate deciduous forest with fluctuating water table. *Soil Biology and Biochemistry* 38: 2527-2535. - doi: [10.1016/j.soilbio.2006.03.009](https://doi.org/10.1016/j.soilbio.2006.03.009)
- Weiss NA (1989). *Elementary statistics*. Addison-Wesley Publishing Company, Massachusetts, USA.
- Zhao M, Zhou J, Kalbitz K (2008). Carbon mineralization and properties of water-extractable organic carbon in soils of the south Loess Plateau in China. *European Journal of Soil Biology* 44: 158-165. - doi: [10.1016/j.ejsobi.2007.09.007](https://doi.org/10.1016/j.ejsobi.2007.09.007)