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Adaptation of Forest Ecosystems to Air Pollution and Climate Change
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Adaptation of forest ecosystems to air pollution and climate change: a global assessment on research priorities

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Climate change and air pollution are two of the anthropogenic stressors that require international collaboration. Influence mechanisms and combating strategies towards them have similarities to some extent. Impacts of air pollution and climate change have long been studied under IUFRO Research Group 7.01 and state of the art findings are presented at biannual meetings. Monitoring, modelling, assessment of multiple stressors, ecophysiology, and nutrient cycles have been thoroughly studied aspects of climate change and air pollution research for a long time under the umbrella of IUFRO RG 7.01. Recently, social and economic issues together with water relations are gaining more attention in parallel with science requirements on adaptation. In this paper, we summarise the main research needs emphasized at the recent 24th IUFRO RG 7.01 Conference titled "Adaptation of Forest Ecosystems to Air Pollution and Climate Change". One important conclusion of the conference was the need for information on nutritional status of forest stands for sustainable forest management. It has been suggested to maintain long-term monitoring programs and to account for the effects of extreme years, and past and present management practices. Long-term monitoring can also help to understand the effects of forestry treatments on the nutrient and water budgets of the ecosystems which may enable to improve management practices like water saving silviculture.

Keywords: IUFRO, Forest research, Forest monitoring, Water budget

Introduction

According to its 4th report; IPCC estimates the global warming at a level of 0.2 °C per decade (IPCC 2007). The consequence of this warming projection corresponds to various climate change scenarios at regional level. Adaptation of ecosystems to climate change is likely to become a more significant part of the issue in the near future. From another perspective; this also means less resistant ecosystems to air pollution in some regions of the world. In fact, the effects of both climate change and air pollution are heterogeneously distributed. Forest ecosystems may be adversely affected in some regions but may benefit from milder climatic conditions or nitrogen fertilizing at some other regions. At this point one important tool that should be prioritized is global networks for monitoring and assessment.

Air pollution and climate change effects on forest ecosystems constitute significant scientific research fields today. Strong scientific research enables healthy forest ecosystems. It has been widely accepted that not only the sustainability of ecosystems but also of communities depends on healthy forests (Pokharel & Larsen 2007).

International policy on environmental problems has never required more scientific research than today. IUFRO is the major provider of scientific research on climate change and air pollution effects on forest ecosystems. Many aspects of this research field are covered by IUFRO research group RG 7.01.00, that is titled "Impacts of Air Pollution and Climate Change on Forest Ecosystems". In this RG, monitoring, indicator development, mechanisms of action, atmospheric deposition, soils and nutrient cycles, ecophysiology, genetics, molecular approaches, multiple stressors, water cycle and water related ecosystem responses, mechanisms of action and response measures, and social and political aspects are existing as active research spots. The interrelations and flow of the mechanism towards solid management solutions are given in Fig. 1.

The scientific research on air pollution and climate change requires long term reliable data of atmosphere, soil, water, and vegetation. These components of ecosystems are monitored and human interphereneces on them are identified as the basis of research. The cumulative effects of multiple stressors like drought, pollution, diseases, fire and insects, changes in moisture and temperature conditions can also be assessed by monitoring. The changes in precipitation and temperature patterns in a region directly affect evapotranspiration which is the key parameter of water budgets of lotic and lentic systems embedded in forest ecosystems. This linkage is vital for the adaptation (Sala & Tenhunen 1993) and biodiversity of forested regions. Water shortage may cause extended dry flow conditions in some regions like the Mediterranean (Tognetti et al. 2000), while excessive rainfall in some parts of Europe and northern US and Canada may result in increase in flooding of streams in forests (Kiely 1999).

In the IUFRO RG 7.01.00, the researches on these aspects of climate change are evaluated towards mechanisms of action and then turn into management strategies and political decisions.

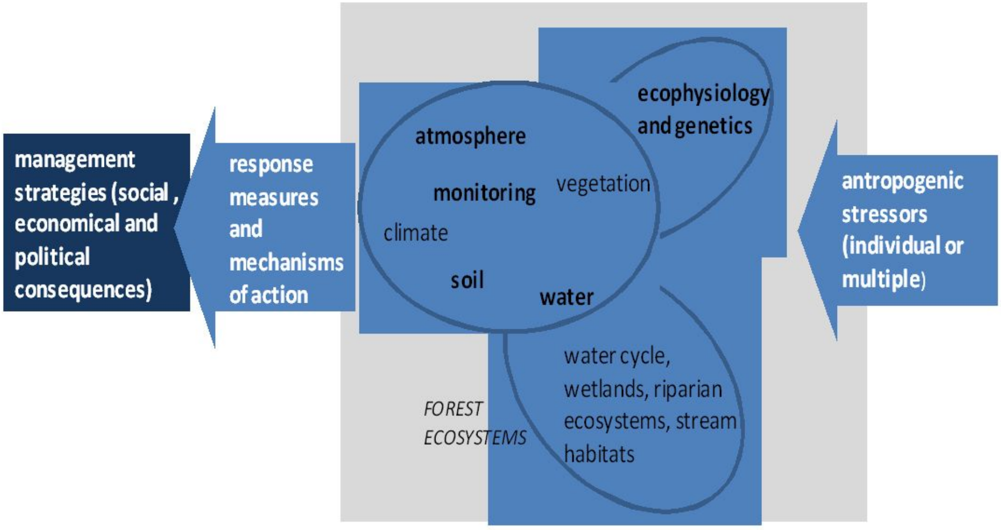

Fig. 1 - The research bridge between effects and measures. The bold terms reflect the study fields of the subdivisions of IUFRO 7.01.00 Research Group.

The aim of this paper is to discuss the research topics on impacts of air pollution and climate change to put forward gaps and priorities as emerging from the 24th IUFRO RG 7.01 conference "Adaptation of Forest Ecosystems to Air Pollution and Climate Change", held in Antalya (Turkey) in March 2010.

Advances in air pollution and climate change impacts research fields

Monitoring

Climate change with increasing air temperature by 3-6 °C over 100 years may affect forest production (Loustau et al. 2005) and forest adaptation to unfavourable environmental conditions such as acid deposition and tropospheric ozone (Ashmore & Bell 1991). To date, however, it is still unclear whether local meteorological conditions affected by climate change will reduce or enhance air pollution effects on forest functioning and health. The Pan-European Program for Intensive and Continuous Monitoring of Forest Ecosystems (UNECE/ICP-Forests) that was implemented to gain a better understanding of the effects of air pollution on forests, has recently started to evaluate not only the direct impact of changes in climatic parameters on forest ecosystem but also on sulphur (S) and nitrogen (N) deposition, soil-mediated parameters and surface ozone concentrations. Their integrated impact on forest ground vegetation (Van Dobben & De Vries 2010), health and increment of the trees in relation to carbon sequestration as well as forest functioning and sustainability is becoming of increasing concern.

Results suggest that despite decreases in the emission of precursor substances (VOC, NO, NO_2), a rise in ozone concentrations is still evident (Paoletti 2007). Tropospheric ozone (O_3) air pollution has been recognized as a major phytotoxic agent since the middle of the last century. Also nitrogen (N) and ammonium (NH_4^+) concentrations and deposition are showing decreasing trends (EEA 2010). Due to enhanced acidification processes in the soil and imbalances in nutrition, however, they still represent one of the key threats to forest ecosystems in the near future, especially in Central and Northern Europe. It has been well documented that N-deposition may affect species diversity of ground vegetation, and increase tree growth (based on N concentration data from foliage and soil solution) and the risk of drought stress and pests (Cannell et al. 1998, Solberg et al. 2009) in certain ecological conditions. In combination, these effects could result in an extreme deterioration of forest conditions. On the other hand, a clear direct impact of N-deposition on crown condition could not be well established and requires further investigations. The lack of long-term monitoring data and the use of short time data series may lead to misinterpretations and, in the context of global change, may contribute to the current uncertainties.

There is a general agreement that atmospheric deposition and soil solution have a medium- to long-term influence and significant cumulative effects on forest conditions and vegetation in the context of global change. An extended and integrated assessment of environmental indicators for global change consistently turns out as one of the most important emerging monitoring and research needs. An improved assessment of environmental indicators for global change should provide an increased knowledge of the diagnostic and mechanistic processes occurring in forest ecosystems and allow a more precise prediction of forest health and the state of forest ecosystems for the current global change scenarios. The seasonal variability of environmental contaminants and the main meteorological parameters such as air temperature and soil water regime are suggested as key research areas for investigating climate change effects on forest ecosystems.

Uncertainties in this field could be reduced by means of assessing tree condition using remote sensing technologies, which emphasize aerial photography, satellite images, and laser scanning for collecting data on forest conditions. Based on the application of hyperspectral cameras, most recent research was conducted in the fields of forest condition assessment, forest inventory, and soil and water quality (Serrano & Penuelas 2005, Xie et al. 2008). These advanced techniques offer new possibilities in sustainable forest management under changing climate, which might help to develop reliable scenarios of climate change and air pollution effects on forest adaptation and mitigation abilities.

Indicator development and mechanisms of action

Ground-level ozone is recognized as a global agent of climate change, which requires merging research on air pollution and changing environment into one common perspective (Paoletti & Manning 2007). The separation between these two research communities needs to be overcome. The argumentation is based on the capacity of ozone to interact in tree and forest ecosystem response with other environmental factors like CO_2, N and drought, even driving below-ground processes and influencing carbon sink strength and pool formation in the entire plant-soil system (Wieser & Havranek 1995, Panek 2004). Effects on competitiveness and stress defence, as mediated through genotype and site conditions, demand for enhanced research efforts on ozone effects on plant competition and biodiversity. In addition, awareness has proceeded recently about ground-level ozone as a local towards trans-continental agent, with new "hot spots" of distinctly enhanced regimes arising both in the northern and southern hemisphere. Conversely, ozone effects on global C fixation and storage remain uncertain, mostly because prognoses suffer from the lack of empirical databases and, hence, rigorous validation of modelling. Integrated research concepts are required that unify modelling with ecologically relevant experimentation on the actual O_3 uptake and the sensitivity per unit of O_3 uptake ("effective dose") in trees and forests, in order to develop robust tools for reliable O_3 risk assessment.

Atmospheric deposition, soils and nutrient cycles

Various aspects of deposition of air pollutants to forests, their effects on watershed chemistry and forest health, and management recommendations for improving sustainability of the impacted ecosystems have been subject to studies on atmospheric deposition and nutrient cycles (Bytnerowicz et al. 2007, Pretzsch et al. 2008). More studies on interactions between science and management present activities where long-term monitoring of N and S deposition and inputs of other toxic pollutants and their effects on multiple watersheds are needed. In modern forest management practices, there is a need for including information on nutritional status of forest stands for sustainable forest management. In that regard, it is imperative to maintain long-term monitoring programs and to account for the effects of extreme years as well as past and present management practices. Improved understanding of N deposition, N leaching, soil acidification and biogeochemical processes in forest stands between forest edges, forest gaps and forest stand interiors may help understanding the stand structure and nutrition interaction (Ritter et al. 2005). Another point is the individual components of the hydrologic cycle. Better understanding of throughfall measurements and interpretation is needed, especially when estimates of the dry component of total deposition are concerned. Importance of N atmospheric dry deposition in arid and semi-arid ecosystems and a need for developing reliable methodologies for its estimates is emphasized.

Forests play a crucial role in the global C cycling acting both as sinks and sources. More reliable methods and data are needed to identify the C compartments of various stand and soil types. Understanding these relationships is mandatory for a better evaluation of C sequestration in forests under various climate change scenarios. Ground-level O_3 has a strong phytotoxic potential and affects abilities of forests to sequester C. Several research groups in Europe and north America have been developing new, physiology-based standards for ozone (Paoletti & Manning 2007). Although environmental problems related to effects of heavy metals are quite limited in Europe and north America, biomonitoring methodologies could be valuable for evaluation of potential effects of heavy metals on forests and other ecosystems in developing areas of Asia, south America or Africa.

Ecological impacts and genetic aspects

The topics of ecological impacts and genetic aspects ranges between the identification of stress indicative genes and the integration of genetic markers in the long-term monitoring of the response of tree populations to various abiotic and biotic stresses.

Generally, the door is wide open for integration of genetic information in the study of ecosystem dynamics ("from gene to environment"). Particularly the fields of molecular genetics and corresponding studies of the function of genes supply a variety of applications. The understanding of complex processes of adaptation and survival of populations under various stress conditions requires synergistic approaches which combine information about gene expression with the large variety of physiological and morphological traits (Longauer et al. 2004). Information on the function of genes of tree species as compared to other plant species is still fragmentary. Filling these gaps in the frame of environmental genetics ("ecosystem genetics") was and still is a major challenge for current and future ecological research.

Impacts of air pollution and climate change on forest ecosystems: multiple stressors and ecosystem services

Research on evaluation of multiple stressors on forest species and ecosystem health and services are emphasized under this topic. Different approaches are possible for assessing multiple stressors, including the use of environmental gradients (Arbaugh et al. 2003) and free air factorial exposures (Paoletti & Grulke 2005), and tools such as stem or sap flow gauges that allow evaluation of chamberless, whole tree responses. Another focus of the subject is to shift the endpoint of interest from individual plant or forest stands to ecosystem functions or services, the latter being society's valuation of the physical and biological functions of ecosystems. Examples of ecosystem services include water quality and quantity, clean air, greenhouse gas mitigation, and habitat protection. Understanding and quantifying ecosystem services requires integrative, interdisciplinary research at several levels of biological organization. The overall goal is to help bring awareness to and to promote investigations at this higher level of physical and biological complexity.

Social and Economic Aspects

Social and economic aspects of forestry research -in relation with air pollution and climate change- is strongly related with the ecosystem services and their evaluation (De Groot et al. 2002). Studies in this field lay between antropogenic influences, ecosystem functions, and ecosystem services concepts. Ecosystems functions are defined as the capacity of natural processes to perform ecosystem services (De Groot et al. 2002) and can be classified as provisioning (wood, non-wood products etc.), regulating (air, water conservation etc.), and cultural (recreational, aesthetics etc.). Demand curve and cost based methods are used to evaluate the loss caused by decreased forest ecosystem services. The ecosystem services may be estimated by various methods (*i.e.*, Biotope valuation method, Energy-water-vegetation method).

A research gap in this field is at the intersection of ecosystem structures-ecosystem services. For example ecosystem services of mixed forests may be quite different than monocultures (Felton et al. 2010). Another point that requires work is the effects of individual events. The dimension and frequency of extreme events are expected to increase particularly due to climate change (Breda & Badeau 2008, Lindner et al. 2010). Therefore, reliable methods are needed to identify social and economic aspects of individual damages towards forests.

Water Cycle

Air pollution and climate change will/may change availability, quality and regime of water resources and therefore forest ecosystems (Kirshbaum 2000 by affecting the water cycle components (Loaiciga et al. 1996, Huntington 2006). Water is a vital major component of ecosystems to shape them (climax vegetation) and to affect their health (drought, nutrient cycles, insects, etc.). The major research topics on the intersection of hydrology and forestry are: drought and floods and their effects; biodiversity affected by hydrologic diversity; evapotranspiration and its components; stream habitats and riparian ecosystems; nutrient cycle-water cycle interaction; precipitation-runoff; Erosion and sedimentation processes in forest ecosystems.

The hot topics of the water-climate change-forest ecosystems research triangle emphasized at the conference have been on the water stress and availability for the forest ecosystems in changing climatic conditions, management options for mitigating water deficit, water consumption of various stand types and tree species, hydrologic modelling of forested watersheds and water resources management options including hydropower plants.

On the other hand, evapotranspiration from forests has always been a major topic of hydrologic cycle (Verstraeten et al. 2005, Overdieck & Forstreuter 1994). Transpiration measurements on individual trees and stands should be incorporated with water budgets to be scaled up for large basins. Precision of watershed models should be increased in order to be used for climate change assessments which could be possible only with precise data on climate, soil, topography, water, and vegetation.

Studies on impacts of air pollution and climate change on aquatic and riparian ecosystems are very few in number (Fortier et al. 2010) and remains as a research gap. In particular, urban forests including riparian corridors along the streams are under high risk of air pollution damage.

The topicality of this issue in air pollution and climate change research is so high that the generation of a new RG 7.01 working party about hydroecology was decided. The main aims of this WP will be encouraging studies more on: Developing Best Forest Management Practices towards mitigating the effects of air pollution and climate change. This includes water saving silviculture, Responses of ecosystems to extreme events like drought and floods (side effects of climate change), Biodiversity influenced by changing hydrologic conditions. Hydrologic diversity and biologic diversity are very closely related subjects and affected from air pollution and climate change, Evapotranspiration and its components in changing climatic conditions or air pollution damages, Stream habitats and riparian ecosystems. This is a very hot topic and number of papers on these subjects is growing huge. The air pollution and climate change part of it is very important, Nutrient cycle-water cycle interaction. This is sometimes ignored but water cycle is the driving mechanism in nutrient cycles, precipitation-runoff. A widely studied subject both by civil engineers and forest hydrologists. The climate change or forest damages affecting this coupling falls into the scope of suggested hydro-ecology WG, Erosion and sedimentation processes in forest ecosystems. Erosion is sometimes a major concern for forests because roads, logging, recreation and many other forestry treatments or activities are becoming sources of erosion. Besides, sedimentation is a mechanism that is shaping stream corridors. These natural or accelerated (by human impacts) processes are affected from changing climatic conditions as well as forest damages caused by air pollution. This in turn affects all stream habitats in a watershed system.

Final recommendations

Research results should be disseminated, integrated, and provided to the decision makers to ensure further support. IUFRO enables these three linkages through scientific meetings. The results of our last meeting in Antalya (Turkey) provided important insights on the research priorities on air pollution, climate change and forestry.

Monitoring of climate, soil, and water as well as vegetation is mandatory to enable sufficient amount of high-quality data for modelling and assessments. These data are vital to observe the responses of ecosystems to anthropogenic stressors particularly climate change. Being the major forestry research organization around the globe, IUFRO has a serious responsibility to provide scientific support for international issues like air pollution, climate change, biodiversity, and desertification.

Modelling techniques should be improved to get more reliable results and estimations. More sophisticated ecosystem models are developed and available but not applicable to many parts of the world due to data requirements. Simplified but reliable models are needed for widespread usage. The models should also have a linkage with management. Better management systems or options may be possible with a better understanding of ecological systems. And finally results should be available to public for taking actions. Public awareness can push decision makers to move.

References

Arbaugh M, Bytnerowicz A, Grulke N, Fenn M, Poth M, Temple P, Miller P (2003). Photochemical smog effects in mixed conifer forests along a natural gradient of ozone and nitrogen deposition in the San Bernardino Mountains. Environment International 29: 401-406. - doi: 10.1016/S0160-4120(02)00176-9

Ashmore MR, Bell JNB (1991). The role of ozone in global change. Annals of Botany 67: 39-48.

Breda N, Badeau V (2008). Forest tree responses to extreme drought and some biotic events: Towards a selection according to hazard tolerance? Comptes Rendus Geosciences 340: 651-662. - doi: 10.1016/j.crte.2008.08.003

Bytnerowicz A, Omasa K, Paoletti E (2007). Integrated effects of air pollution and climate change on forests: a northern hemisphere perspective. Environmental Pollution 147: 438-445. - doi: 10.1016/j.envpol.2006.08.028

Cannell MGR, Thornley JHM, Mobbs DC, Friend AD (1998). UK conifer forests may be growing faster in response to increased N deposition, atmospheric CO_2 and temperature. Foresty 71: 277-296. - doi: 10.1093/forestry/71.4.277

De Groot RS, Alkemade R, Braa, L, Hein L, Willemen L (2010). Challenges in integrating the concept of ecosystem services and values in landscape planning, management and decision making. Ecological Complexity 7: 260-272. - doi: 10.1016/j.ecocom.2009.10.006

De Groot RS, Wilson MA, Boumans RMJ (2002). A typology for the classification, description and valuation of ecosystem functions, goods and services. Ecological Economics 41: 393-408. - doi: 10.1016/S0921-8009(02)00089-7

Felton A, Lindbladh M, Brunet J, Fritx O (2010). Replacing coniferous monocultures with mixed-species production stands: an assessment of the potential benefits for forest biodiversity in northern Europe. Forest Ecology and Management 260: 939-947. - doi: 10.1016/j.foreco.2010.06.011

Fortier J, Gagnon D, Truax B, Lambert F (2010). Nutrient accumulation and carbon sequestration in 6-year-old hybrid poplars in multiclonal agricultural riparian buffer strips. Agriculture, Ecosystems and Environment 137: 276-287. - doi: 10.1016/j.agee.2010.02.013

Huntington TG (2006). Evidence for intensification of the global water cycle: Review and synthesis. Journal of Hydrology 319: 83-95. - doi: 10.1016/j.jhydrol.2005.07.003

IPCC (2007). Fourth assessment report. The physical science basis. Web site. [online] URL: http://www.ipcc.ch/publications_and_data/ar4/wg1/en/spmsspm-projections-of.html

Kiely G (1999). Climate change in Ireland from precipitation and streamflow observations. Advances in Water Resources 23: 141-151. - [online]: URL: 10.1016/S0309-1708(99)00018-4

Kirshbaum MUF (2000). Forest growth and species distribution in a changing climate. Tree Physiology 20: 309-322. - doi: http://treephys.oxfordjournals.org/content/20/5-6/309.short

Lindner M, Maroschek M, Netherer S, Kremer A, Barbati A, Garcia-Gonzalo J, Seidl R, Delzon S, Corona P, Kolstrom M, Lexer MJ, Marchetti M (2010). Climate change impacts, adaptive capacity, and vulnerability of European forest ecosystems. Forest Ecology and Management 259: 698-709. - doi: 10.1016/j.foreco.2009.09.023

Loaiciga HA, Valdez JB, Vogel R, Garvey J, Schwarz H (1996). Global warming and the hydrologic cycle.Journal of Hydrology 174 (1-2): 83-127. - doi: 10.1016/0022-1694(95)02753-X

Longauer R, Gomory D, Paule L, Blada I, Popescu F, Mankovska B, Mueller-Starck G, Schubert R, Percy K, Szaro RC, Karnosky DF (2004). Genetic effects of air pollution on forest tree species of the Carpathian Mountains. Environmental Pollution 130: 85-92. - doi: 10.1016/j.envpol.2003.10.023

Loustau D, Bosc A, Colin A, Ogee J, Davi H, Francois C, Dufrene E, Deque M, Cloppet E, Arrouays D, Le Bas C, Saby N, Pignard G, Hamza N, Granier A, Breda N, Ciais P, Viovy N, Delage F (2005). Modeling climate change effects on the potential production of French plains forests at the sub-regional level. Tree Physiology 25: 813-823. - doi: http://treephys.oxfordjournals.org/content/25/7/813.short

Overdieck D, Forstreuter M (1994). Evapotranspiration of beech stands and transpiration of beech leaves subject to atmospheric CO_2 enrichment. Tree Physiology 14: 997-1003. - doi: 10.1093/treephys/14.7-8-9.997

Panek J (2004). Ozone uptake, water loss and carbon exchange dynamics in annually drought-stressed *Pinus ponderosa* forests: measured trends and parameters for uptake modeling. Tree

Physiology 24: 277-290. - doi: 10.1093/treephys/24.3.277

Paoletti E, Grulke N (2005). Does living in elevated CO_2 ameliorate tree response to ozone? A review on stomatal responses. Environmental Pollution 137: 483-493. - doi: 10.1016/j.envpol.2005.01.035

Paoletti E, Manning WJ (2007). Toward a biologically significant and usable standard for ozone that will also protect plants. Environmental Pollution 150: 85-95. - doi: 10.1016/j.envpol.2007.06.037

Pokharel RK, Larsen HO (2007). Local *vs* official criteria and indicators for evaluating community forest management. Forestry 80 (2): 183-192. - doi: 10.1093/forestry/cpm005

Pretzsch H, Grote R, Reineking B, Rötzer TH, Seifert ST (2008). Models for forest ecosystem management: a european perspective. Annals of Botany 101: 1065-1087. - doi: 10.1109/PMA.2006.16

Ritter E, Dalsgaard L, Einhorn KS (2005). Light, temperature and soil moisture regimes following gap formation in a semi-natural beech-dominated forest in Denmark. Forest Ecology and Management 206: 15-33. - doi: 10.1016/j.foreco.2004.08.011

Sala A, Tenhunen JD (1993). Site-specific water relations and stomata1 response of *Quercus ilex* in a Mediterranean watershed. Tree Physiology 14: 601-617. - doi: 10.1093/treephys/14.6.601

Serrano L, Penuelas J (2005). Assessing forest structure and function from spectral transmittance measurements: a case study in a Mediterranean holm oak forest. Tree Physiology 25: 67-74. - doi: 10.1093/treephys/25.1.67

Solberg S, Dobbertin M, Reinds GJ, Lange H, Andreassen K, Fernandez PG, Hildingsson A, De Vries W (2009). Analyses of the impact of changes in atmospheric deposition and climate on forest growth in European monitoring plots: A stand growth approach. Forest Ecology and Management 258: 1735-1750. - doi: 10.1016/j.-foreco.2008.09.057

Tognetti R, Minnocci A, Penuelas J, Raschi A, Jones MB (2000). Comparative field water relations of three Mediterranean shrub species co-occuring at a natural CO_2 vent. Journal of Experimental Botany 51 (347): 1135-1146. - doi: 10.1093/jexbot/51.347.1135

Van Dobben H, De Vries W (2010). Relation between forest vegetation, atmospheric deposition and site conditions at regional and European scales. Environmental Pollution 158: 921-933. - doi: 10.1016/j.envpol.2009.09.015

Verstraeten WW, Veroustraete F, Feyen J (2005). Estimating evapotranspiration of European forests from NOAA-imagery at satellite overpass time: towards an operational processing chain for integrated optical and thermal sensor data products. Remote Sensing of Environment 96: 256-276. - doi: 10.1016/j.rse.2005.03.004

Wieser G, Havranek WM (1995). Environmental control of ozone uptake in *Larix decidua* Mill.: a comparison between different altitudes. Tree Physiology 15: 253-258. - doi: 10.1093/treephys/15.4.253

Xie Y, Sha Z, Yu M (2008). Remote sensing imagery in vegetation mapping: a review. Journal of Plant Ecology 1: 9-23. - doi: 10.1093/jpe/rtm005