Item 5

2013 Executive Summary

A. Factors explaining health and vitality of eleven European tree species

1. Defoliation is one of the most important parameters assessed by the International Cooperative Programme on Assessment and Monitoring of Air Pollution Effects on Forests (ICP Forests) for monitoring of forest health and vitality. It is assessed annually at the large scale and is an estimate for leaf or needle loss in comparison to a fully foliated reference tree. For the present study, information on factors influencing defoliation was available from the forest condition and soil data bases of the programme (general site characteristics such as pH, soil chemistry,) as well as from external meteorological data bases. Meteorological parameters (yearly cumulated precipitation, mean temperature, days with daily temperature above 20°C or below 0°C) were taken from the European Centre for Medium-Range Weather Forecast (ECMWF). Nutrient nitrogen critical loads have been estimated from measured soil data. Deposition and critical load exceedances were modelled using the GAINS-EUROPE model.

2. Predictors affecting defoliation were determined through a statistical approach called Random Forest Analysis (RFA). This non-linear approach, allows the identification of variables that contain important predictive power. It produces a relative ranking of factors that contribute to the explanation of defoliation.

3. The Random Forest Analysis has been performed on 11 species, abundant enough for a robust and significant statistical analysis, and the importance of the predictors has been determined separately for each of the considered years. The analysis has been conducted for the following trees: birch (*Betula pendula)*, hornbeam (*Carpinus betulus)*, black pine (*Pinus nigra)*, Scots pine (*Pinus sylvestris)*, pubescent oak (*Quercus pubescens)*, beech (*Fagus sylvatica)*, ash (*Fraxinus excelsior)*, Norway spruce (*Picea abies)*, holm oak (*Quercus ilex)*, sessile oak (*Quercus petraea)* and European oak (*Quercus robur)*.

4. Depending on the tree species the observed defoliation could to varying extents be explained by meteorology, by site and soil parameters as well as by deposition and exceedances of critical loads for nitrogen deposition. For Tables 1-3 predictors were partly grouped into categories like temperature (including days > 20°, days <0°, mean temperature), soil variables (C/N, pH), nitrogen deposition (NOx, NH4). Only those groups or single predictors are shown that were among the three most important ones for each of the tree species in the respective years.

5. For a number of tree species like beech, birch, Scots pine and holm oak the statistical importance of geographical coordinates in all three years indicates regional patterns in defoliation. Soil characteristics are of major importance for hornbeam, black pine and pubescent oak, whereas for four out of 11 species they are not ranked among the first three most important predictors. Modelled nitrogen deposition was among the most important predictors for eight species specifically in 2001. In seven species it is listed in at least two of the three years. This is a new finding, as in previous evaluations it was not possible to show such an importance of nitrogen deposition for forest health indicators such as defoliation. Previously published results were, however, mostly based on linear approaches, whereas the Random Forest Analyses take into account the interrelations between all analysed predictors. Only in two species (Fraxinus excelsior and Pinus nigra), and only in one year critical loads exceedances are important for defoliation. This

might be due to the fact that critical loads and thus also their exceedances refer to a static concept that does not take into account temporal developments such as damage delay. The importance of meteorological variables such as temperature extremes, mean temperature and precipitation for forest health has been well known since the start of the monitoring programme. Interestingly temperature indicators are not related to defoliation for the two tree species that are adapted to warm climates, namely black pine and holm oak. For holm oak precipitation is however important.

Table 1: Importance of geographical coordinates and soil characteristics for defoliation of 11 tree species obtained by RFA.

	Latitude/Longitude			**Soil characteristic**		
Species	**2001**	**2006**	**2011**	**2001**	**2006**	**2011**
birch	X	X	X			
hornbeam		X		X	X	X
beech	X	X	X		X	
ash						
Norway spruce	X		X			
black pine	X			X	X	X
Scots pine	X	X	X			
holm oak	X	X	X	X		
sessile oak	X		X		X	
pubescent oak		X	X			X
European oak			X	X	X	

Table 2: Importance of nitrogen deposition and exceedances of critical nitrogen deposition loads for defoliation of 11 tree species obtained by RFA.

	Nitrogen deposition			**Critical load exceedances**		
Species	**2001**	**2006**	**2011**	**2001**	**2006**	**2011**
birch	X	X	X			
hornbeam		X	X			
beech						
ash	X	X	X	X		
Norway spruce	X					
black pine	X	X	X		X	
Scots pine	X	X				
holm oak						
sessile oak	X					
pubescent oak	X		X			
European oak	X	X				

Table 3: Importance of temperature and cumulated precipitation for defoliation of 11 tree species obtained by RFA.

	Temperature indicators			Cumulated precipitation		
Species	**2001**	**2006**	**2011**	**2001**	**2006**	**2011**
birch		X	X			
hornbeam	X		X	X		
beech	X	X	X			
ash	X	X	X			X
Norway spruce		X	X			X
black pine						
Scots pine		X	X			
holm oak				X		X
sessile oak	X		X		X	
pubescent oak	X	X	X		X	
European oak			X			

6. Results show inter-annual variability. Temperature indicators were e.g. more important in 2011, whereas nitrogen deposition had stronger effects in 2001. As ecological influences are interacting it is clear that the relative importance of a single predictor depends on the specific occurrence of other influences. The applied RFA approach takes these interactions into account.

7. Information on influencing factors is a prerequisite to adapt effective silvicultural and forest management measures. The data and the models applied will allow estimating future defoliation under different climate and air pollution scenarios. This will give information on effectiveness of air pollution abatement measures on one hand and will offer benefits for a meaningful forest management in addition.

B. Forest soil carbon stocks

1. A new benchmark for European forest soil carbon stocks

8. Soil is the largest terrestrial pool of organic carbon. It contains more C than the biosphere and atmosphere together (Batjes, 1996; Schlesinger, 1997; Grace, 2004). Since soils contain (at least) more than twice the C found in the atmosphere, loss of C from soils can have a significant effect on atmospheric CO_2 concentration, and thereby on climate (Smith, 2008). The response of SOC to global warming is, therefore, of critical importance.

9. Forest soils are a major reserve of terrestrial C stock. Roughly about 30% of the global land area consists of forest soils. In absolute terms, the extent of forest soils is greatest in “continental”

Europe (~1000 Mha), accounting for 27% of the global forest soil extent (FOREST EUROPE UNECE FAO, 2011). In this study however, the focus is only on a fraction of this European forest area (i.e. ~163 Mha), since the vast forest areas of the Russian Federation (> 800 Mha) are not included.

10. Prentice (2001) estimated the world's forest soil carbon stocks at 704 Gt C out of ~1500 Gt C for all soils (Jobbagy & Jackson, 2000), consisting of 213 Gt C (30%) in tropical forests, 153 Gt C (22%) in temperate forests and 338 Gt C (48%) in boreal forests. Average soil carbon stocks (till 1 m depth) are 122 t C ha^{-1}, 147 t C ha^{-1} and 296 t C ha^{-1} for tropical, temperate and boreal forests, respectively (Prentice, 2001; Lal, 2005). Thus, forest soils store roughly about half of the terrestrial SOC stock with the largest C densities in boreal forest soils. The latter is partly explained by the relatively high occurrence of peat soils in this region.

11. Despite the tremendous importance of accurate estimation of EU forest soil carbon stocks, only few studies reported SOC estimates at the European level (Baritz *et al.*, 2010). The areal extent and the methodology for these estimations vary greatly, and until now, did not allow to set a reliable benchmark.

12. Based on the 2nd Forest Soil condition survey, conducted between 2004 and 2009 during the EU Forest Focus BioSoil demonstration programme (Hiederer *et al.*, 2011), soil samples from 4928 ICP Forests level I plots of 22 European countries (Figure 1) were collected and analysed.

13. For the first time, variables essential for reliable carbon stock estimations were effectively quantified using harmonized methods: bulk density, coarse fragments, limiting soil depth along with carbon concentrations of all mineral and organic layers up to 80 cm of depth. Compared to the dataset of the first European forest soil survey (1985-1996) reported by Vanmechelen *et al.* (1997) and used for carbon quantifications by Baritz *et al.* (2010), the current forest soil dataset (FSCDB.LI.2.1) is much more complete and adequate. About half of the Level I plots assessed during the BioSoil survey were also sampled during the first survey, albeit with variable sampling schemes and diverging analytical methods, complicating assessment of carbon stock changes over time. This will be our next challenge.

14. The carbon stocks in the forest floor could be estimated for 82% of all level I plots (Figure 1). Average OC pools in terrestrial humus forms range from 8 t C ha^{-1} in Mull types to 22.5 t C ha^{-1} in Mor types, and from 19.6 to 74.4 t C ha^{-1} in semi-terrestrial (wet) humus forms. Histomoders and Histomors store over two to three times more OC than Moders and Mors, respectively. In all, the OC stock of European forest floors reveal an estimated median value of 13.8 t C ha^{-1} and a mean of 22.1 t C ha^{-1}. When upscaling the plot based averages to the European level, forest floors store

about 3 Gt carbon in all surveyed countries (135 Mha of forest). Extrapolated to a European reference forest area of 163 Mha, this amounts to 3.66 Gt C.

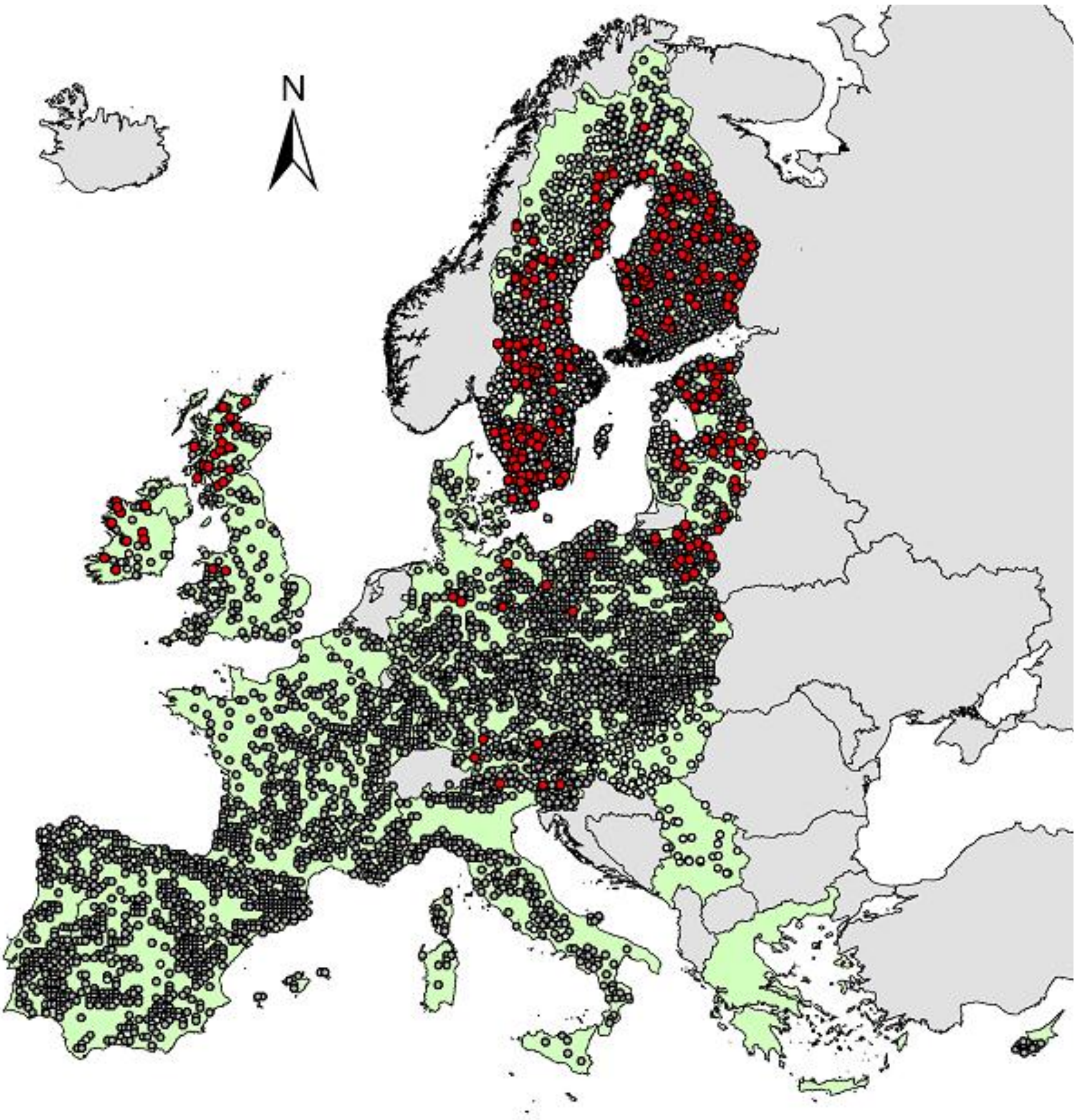

Figure 1. Map of surveyed countries (green) and their systematic Level I plots (O). Plots where 1-m SOC stocks could be quantified are filled in grey. Red dots shows afforested peat soils as carbon 'hot spots'.

15. Excluding Histosols (peat soils), the average carbon stocks in mineral soils is 64.9 t C ha^{-1} till 30 cm of depth, ranging from 10.8 to 176 t C ha^{-1} (95% range). To 100 cm or effective soil depth the average SOC stock is 108 t C ha^{-1}, with 95% of all SOC stocks comprised within 15.5 and 349 t C ha^{-1}. For the Histosols the average 0-30 cm stock is 186 t C ha^{-1} (95% range: 25 – 383) and for 0-100 cm depth 578 t C ha^{-1}, with 95% of these plots ranging from 63.1 to 1159 t C ha^{-1} depending on peat thickness.

16. Generally, 30-cm C stocks represent 44-66% of total 1-m stocks in mineral soils whereas only 32% in peat soils, indicating distinct and specific depth profiles between mineral and organic soils. In all, about 50% of the 1-m stock is stored in the upper 20 cm, and ~22%, ~12%, ~10% and ~7.5% in the subsequent 20-cm intervals. Since carbon stored in the forest floor and topsoil (< 20 cm) is much less sequestered compared to deeper layers (Trumbore *et al.*, 1996), roughly half of the 1-m carbon stock might become a source of CO_2 to the atmosphere upon deforestation or due to severe climatic changes, causing in turn a positive feedback mechanism to global warming.

17. When upscaling the SOC stocks to the European level, the 1-m stock in the surveyed countries (135 Mha) is 18.03 Gt C and 21.8 Gt C for the European union (163 Mha). Confidence intervals for each of these estimates and a description of the calculation methods is given in De Vos *et al.* (in prep). Relative to the estimates of Prentice (2001), the forest soils' carbon reservoir in our study area represents only ~3% of the global forest SOC stock and ~14% of the one of temperate forests. The total European SOC reservoir is estimated at ~75 Gt C by the CLIMSOIL report (EC, 2008). If that estimate is correct, we found that 34% of that pool is stored in forest soils (including forest floor).

18. Our study clearly shows that the carbon stored in forest floors should not be neglected as in most carbon accounting efforts, since it represents ~17% of the 1-m forest soil stock. The carbon stored in EU forest floors is 3.3 times the total C emitted each year from the combustion of fossil fuel in Europe (based on CLIMSOIL data).

19. Though the areal extent of afforested peatsoils (Histosols) is limited (i.e. between 7.4 and 8.8 Mha), they store between 4.3 and 5.3 Gt C. Hence on ~5% of the forest area, 20-24% of the total forest soil carbon stock is stored in these peat soils, underscoring their importance for preservation and wherever possible, for their extension.

20. At the European scale, the factors explaining the carbon stock in the forest floor are mainly humus type, soil type and tree species and to a lesser extent climatic variables. For the carbon stock in the soil, soil type is the dominant predictor, followed by mean annual precipitation. The future holds promise to further explore this EU soil carbon dataset, predominantly for calibration

and validation of (forest) soil carbon models and comparison with legacy and future soil carbon datasets.

2. C:N ratio

21. The C:N ratio is considered as an indicator of nitrate leaching in coniferous forests in response to high atmospheric nitrogen (N) deposition (Dise et al., 1998; Emmett et al., 1998; Gundersen et al., 1998; Macdonald et al., 2002).

22. In deciduous forests with thin forest floors, the C:N ratio of the mineral topsoil was shown to be a better indicator (Vesterdal et al., 2008; Gundersen et al., 2009). However, the C:N ratio is influenced by a multitude of other site-related factors.

23. During the second soil survey on the ICP Forests Level I network (De Vos and Cools, 2011), very high C:N values in the forest floor have been recorded both in Northern (Finland and Sweden) and in Southern Europe, particularly in Portugal and Spain (Figure 2). Ninety-five per cent of the C:N ratios were between 16 and 44 in the forest floor, between 13 and 44 in the peat topsoil and between 10 and 32 in the mineral topsoil. Within the terrestrial forest floor and mineral soil, the C:N ratios decreased with depth, while in the hydromorphic forest floor and the peats no clear trend with depth was observed.

24. A boosted regression tree analysis (Elith et al., 2008) on 15 site and environmental variables (Table 1), showed that tree species is the most important explanatory variable for the C:N ratios of the forest floor and the upper mineral soil (Cools et al. 2013) at the European level.

25. Black locust and black alder, both nitrogen fixing tree species, show mean forest floor C:N ratios below 20.While in Northern Europe Scots pine shows very high C:N values (mean 30), tree species like maritime, lodgepole, Aleppo and black pine but also broadleaved evergreen species like eucalyptus and cork oak show mean C:N ratios above 30 in Southern Europe. In the deeper mineral soil layers, soil type was the most important explanatory variable. Deposition and climatic variables were of minor importance at the European scale. Following the N status classes as defined by Gundersen et al. (2006), about one third of the coniferous sites had high N status, one third intermediate and one third low N status (Table 2).

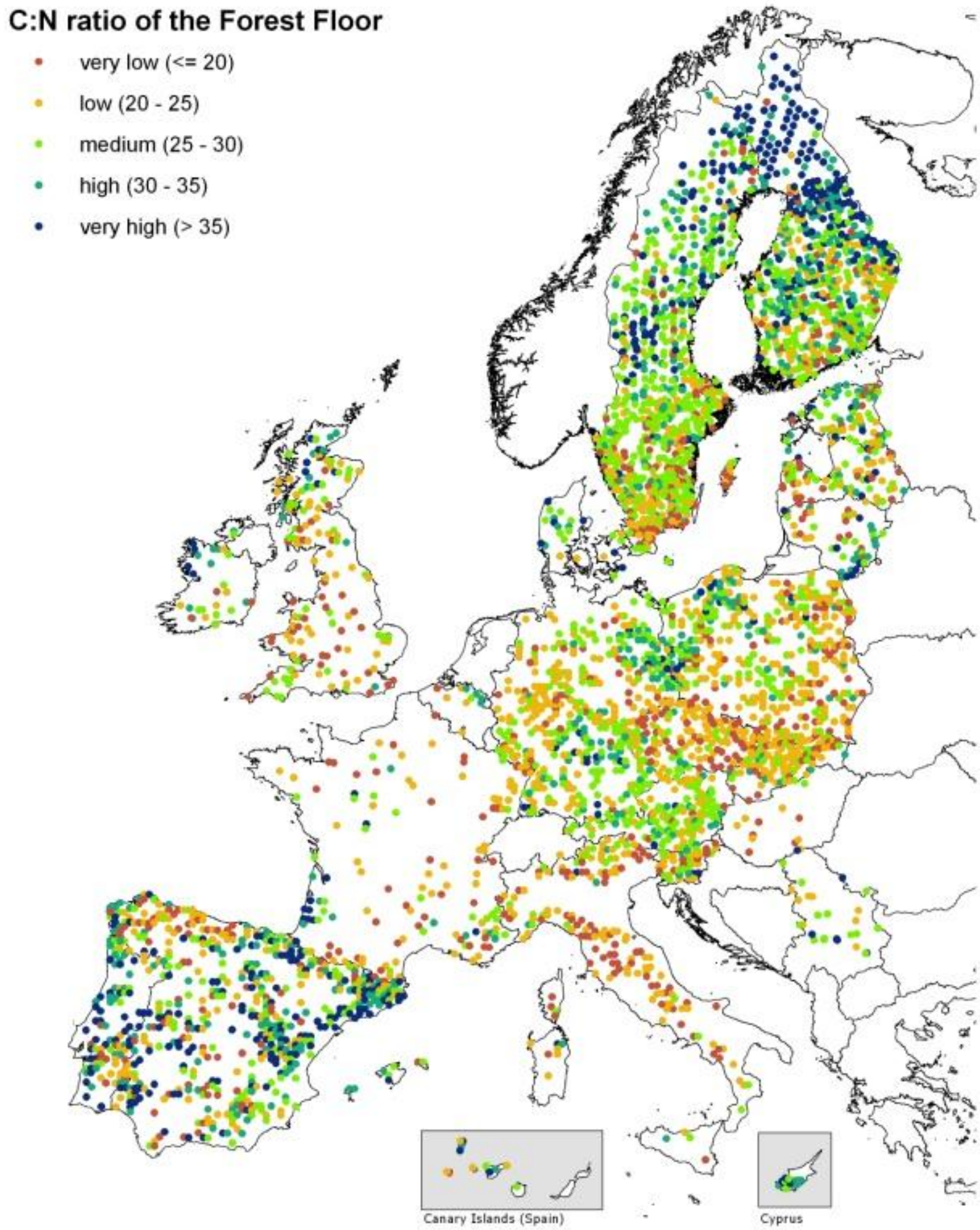

Figure 2: C:N ratio of the forest floor on 3837 plots of the ICP Forests Level I network

Table 1: Environmental variables used in the boosted regression tree analysis

Variable	Type	Description
Latitude, Longitude	numeric	X and Y coordinates of the site
Altitude	numeric	Elevation above sea level
MAT	numeric	Mean annual temperature
MAP	numeric	Mean annual precipitation
Parent Material	factor (9)*	Parent material class
WRB RSG	factor (26)	WRB reference soil group (IUSS Working Group WRB 2007)
Soil depth	numeric	Estimated depth of profile (till 100 cm)
Humus type	factor (9)	Amphi, mull, moder, mor, anmoor, histoamphi, histomull, histomoder or histomor
Forest type	factor (12)	Forest type (FOREST EUROPE, UNECE & FAO, 2011)
Tree species	factor (25)	Tree species code of main tree species
Ecoregion	factor (18)	Ecoregion (EEA, 2004)
NredTOT NoxTOT SoxTOT	numeric numeric numeric	Total (dry+wet) depositions for reduced and oxidised N and oxidised S by the EMEP/MSC-W model cumulative totals for the years 2002- 2006

*number of levels

Table 2: The number of coniferous ICP Forests plots on Level I by main coniferous tree species with high, intermediate and low N status according to the C:N ratio of the forest floor (Gundersen et al., 2006)

	N plots	High N status	Intermediate N status	Low N status
		C:N < 25	25 ≤ C:N ≤ 30	C:N > 30
Scots pine	1291	326 (25%)	431 (33%)	534 (41%)
Norway spruce	927	425 (46%)	368 (40%)	134 (15%)
Maritime pine	103	10 (9.7%)	20 (19%)	73 (71%)
Aleppo pine	90	20 (22%)	28 (31%)	42 (47%)
All coniferous stands	*2745*	*924 (34%)*	*922 (34%)*	*899 (33%)*

26. Further analysis for eight main forest tree species individually, showed that the influence of environmental variables on C:N ratios was tree species dependent. For Aleppo pine and holm oak, both with a typical Mediterranean distribution, the relationship between N and S deposition and C:N ratio appeared to be positive. This study suggests that applying C:N ratios as a general indicator of the N status in forests at the European level, without explicitly accounting for tree species, is probably too simplistic. The intensive monitoring could offer a better insight into the potential relationship between tree species and risk for nitrate leaching.

2. Status of pH and base saturation

2.1 pH

27. The pH($CaCl_2$) in the top 10 cm of the mineral forest soil ranges from 2.5 to 7.8 where 95% of the pH values are situated between 3.0 and 7.4. The median value is 4.0 and the mean 4.5, although most observations are comprised within the 3.75 – 4.0 class. The pH shows a bimodal distribution where the calcareous soils show a second peat within the pH 7.0 – 7.5 range which is seen on all depths. In the mineral soils, the pH gradually increases with depth. There is a clear gradient in increasing pH($CaCl_2$) in the upper 10 cm of the mineral and peat soils from Northwest to Southeast Europe except for some slight calcareous areas in Estonia and Latvia (Figure 2).

2.2 Base Saturation

28. The base saturation, calculated as the proportion of basic exchangeable cations (Ca^{2+}, Na^{+}, Mg^{2+} and K^{+}) to the cation exchange capacity of the soil, is considered as a measure for the buffering capacity of the soil against soil acidification. The buffering capacity indicates how resistant the soil is to attempts of changing its pH. When the base saturation is depleted below levels of 10–20%, the remaining basic cations are more tightly held and are less available for counteracting soil acidification (Reuss and Johnson, 1986; Ulrich, 1995).

29. A gradient from very low base saturation in Northern Europe to low values in Central-Eastern Europe, over moderate base saturation in Central-Western Europe to high values in Southern Europe can be explained by natural conditions such as the presence of acidic Podzols in Northern Europe, sandy soils (Arenosols) in the Central-East of Europe (mainly Poland) and the calcareous parent material in Southern Europe. Figure 4 shows the status of the base saturation in the upper 10 cm of the mineral soil in the second soil survey. The

classes with base saturation below 10–20% indicate forest soils with low buffering capacity against soil acidification.

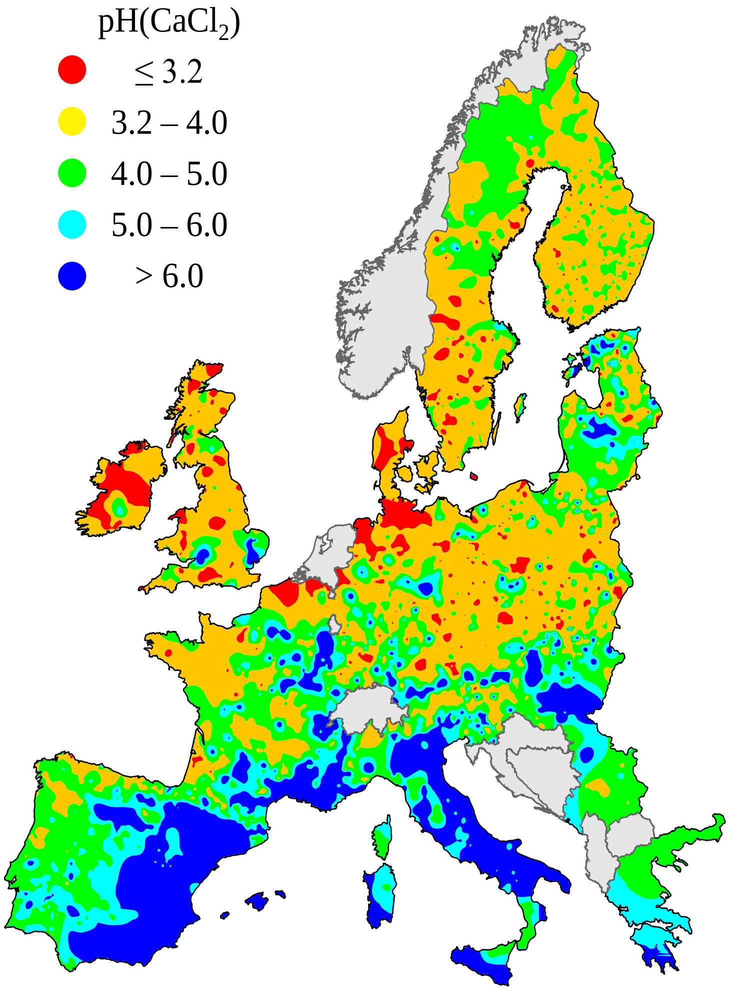

Figure 3: Kriged map of the pH($CaCl_2$) in the upper 10 cm of mineral soils and peat soils of the ICP Forest Level I and Level II plots assessed during the BioSoil survey

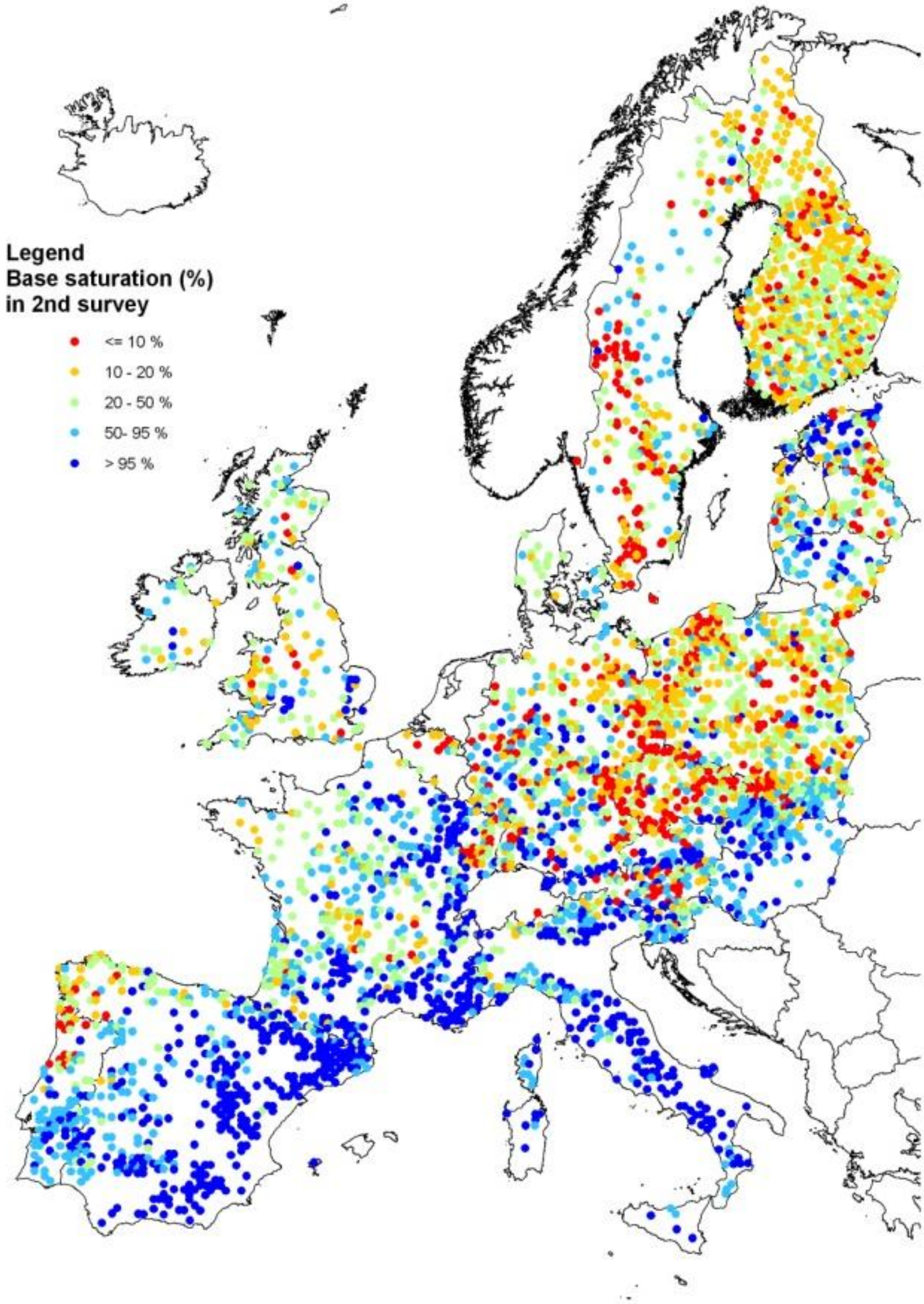

Figure 4: Base saturation in the upper 10 cm of mineral soils of the Level I plots assessed during the BioSoil survey

References

Baritz, R., Seufert, G., Montanarella, L. & Van Ranst, E. 2010. Carbon concentrations and stocks in forest soils of Europe. *Forest Ecology and Management,* 260, 262-277.

Batjes, N. H. 1996. Total carbon and nitrogen in the soils of the world. *European Journal of Soil Science,* 47, 151-163.

Cools, N., Vesterdal, L., De Vos, B., Vanguelova, E., Hansen, K. 2013. Tree species is the major factor explaining C:N ratios in European forest soils (submitted in revised form to For. Ecol. Manage. 18-04-2013).

De Vos, B., Cools, N. 2011. Second European Forest Soil Condition Report: results of the BioSoil Soil inventory. INBO.R.35.2011. Research Institute for Nature and Forest, Belgium.

Dise, N.B., Matzner, E., Forsius, M., 1998. Evaluation of organic horizon C:N ratio as an indicator of nitrate leaching in conifer forests across Europe. Environ. Pollut. 102: 453-456.

EC, 2008. CLIMSOIL: Review of existing information on the interrelations between soil and climate change. Technical Report - 2008 – 048. European Communities. Available at: http://ec.europa.eu. 212 p.

EEA, 2004. Ecoregions for rivers and lakes. [http://www.eea.europe.eu/data-and-maps/data/ecoregions-for-rivers-and-lakes]

Emmett, B.A., Boxman, D., Bredemeier, M., Gundersen, P., Kjønaas, O.J., Moldan, F., Schleppi, P., Tietema, A., Wright, R.F., 1998. Predicting the Effects of Atmospheric Nitrogen Deposition in Conifer Stands: Evidence from the NITREX Ecosystem-Scale Experiments. Ecosystems 1: 352-360.

Elith, J., Leathwick, J.R., Hastie, T., 2008. A working guide to boosted regression trees. J. Anim. Ecol. 77: 802-813.

FOREST EUROPE, UNECE, FAO, 2011. State of Europe's Forests 2011. Status and Trends in Sustainable Forest Management in Europe. 337 pp.

Grace, J. 2004. Understanding and managing the global carbon cycle. *Journal of Ecology,* 92, 189-202.

Gundersen, P., Callesen, I., de Vries, W., 1998. Nitrate leaching in forest ecosystems is related to forest floor C:N ratios. Environ. Pollut. 102: 403-407.

Gundersen, P., Sevel, L., Christiansen, J.R., Vesterdal, L., Hansen, K., Bastrup-Birk, A., 2009. Do indicators of nitrogen retention and leaching differ between coniferous and broadleaved forests in Denmark? For. Ecol. Manage. 258: 1137-1146.

Hiederer, R., Micheli, E. & Durrant, T. 2011. Evaluation of the BioSoil Demonstration Project. Soil Data Analysis. In., JRC Scientific and Technical reports. EUR 24729 EN , Publication Office of the European Union, pp. 155.

IUSS Working Group WRB, 2007. World Reference Base for Soil Resources 2006, first update 2007. 116 pp. FAO, Rome.

Jobbagy, E. G. & Jackson, R. B. 2000. The vertical distribution of soil organic carbon and its relation to climate and vegetation. *Ecological Applications,* 10, 423-436.

Lal, R. 2005. Forest soils and carbon sequestration. *Forest Ecology and Management,* 220, 242-258.

MacDonald, J.A., Dise, N.B., Matzner, E., Armbruster, M., Gundersen, P., Forsius, M., 2002. Nitrogen input together with ecosystem nitrogen enrichment predict nitrate leaching from European forests. Global Change Biol. 8: 1028-1033.

Prentice, I. C. 2001. The carbon cycle and atmospheric carbon dioxide. In: *Climate Change 2001: The Scientific Basis.* (ed IPCC), Cambridge University Press, Cambridge, UK, pp. 183-237.

Reuss J.O. and Johnson D.W. 1986. Acid Deposition and the Acidification of Soils and Waters. Ecological Studies 59. Springer-Verlag. 120 pp.

Schlesinger, W. H. 1997. *Biogeochemistry, an analysis of Global Change,* Academic Press, San Diego, California.

Smith, P. 2008. Land use change and soil organic carbon dynamics. *Nutr Cycl Agroecosyst,* 81, 169-178.

Trumbore, S. E., Chadwick, O. A. & Amundson, R. 1996. Rapid exchange between soil carbon and atmospheric carbon dioxide driven by temperature change. *Science,* 272, 393-396.

Ulrich B. 1995. The history and possible cause of forest decline in central Europe, with particular attention to the German situation. Environmental Reviews 3: 262 – 275.

Vanmechelen, L., Groenemans, R. & Van Ranst, E. 1997. Forest Soil Condition in Europe: results of a large scale soil survey. In., EC, UN/ECE and Ministry of the Flemish Community, Brussels, Geneva, pp. 261.

Vesterdal, L., Schmidt, I.K., Callesen, I., Nilsson, L.O., Gundersen, P., 2008. Carbon and nitrogen in forest floor and mineral soil under six common European tree